

# Maintenance Procedures and Practices for Underground Mobile Mining Equipment

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MSc Thesis

# Maintenance Procedures and Practices for Underground Mobile Mining Equipment

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# ABSTRACT

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Worldwide, underground mines mobile equipments are the most critical units in the mine production systems to ensure continuous flow of ore. Mining companies face challenges in reduction of operational cost, capital cost and maintaining high production level in this world of fast dynamic technological advancement, equipments/systems enormousness and complexity as well as ongoing attempts to automate production equipments. High equipments availability, safety, maintainability and controllable reliability become an important issue.

This thesis focuses on maintenance procedures and practices for mobile mining equipment in the context of underground mining environment with the main goal of identification of major causes of equipment breakdown, identification of maintenance problems and evaluation of computerized maintenance management system data handling at LKAB (Malmberget mine) and Barrick Gold Tanzania (Tulawaka mine) and if possibly to suggest measures for improvement. The data have been presented and the efficiency of the existing maintenance management system has been discussed and illustrated for each case study area, finally the measures for improvement have been suggested.



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# BASIC DEFINITIONS

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**Maintenance** – Combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function.

**Maintenance plan** – Structured set of tasks that include the activities, procedures, resources and the time scale required to carry out maintenance.

**Availability (performance)** – Ability of an item to be in a state to perform a required function under given conditions at a given instant of time or during a given time interval, assuming that the required external resources are provided.

**Reliability** – Ability of an item to perform a required function under given conditions for a given time interval

**Maintainability** – Ability of an item under given conditions of use, to be retained in, or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources.

**Failure** – Termination of the ability of an item to perform a required function.

**Preventive maintenance** – Maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item.

**Condition based maintenance** – Preventive maintenance based on performance and/or parameter monitoring and the subsequent actions.

**Predictive maintenance** – Condition based maintenance carried out following a forecast derived from the analysis and evaluation of significant parameters of the degradation of the item.

**Corrective maintenance** – Maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function.

**Deferred maintenance** – Corrective maintenance which is not immediately carried out after a fault detection but is delayed in accordance with given maintenance rules

**Operator maintenance** – Maintenance carried out by a user or operator.

**Inspection** – Check for conformity by measuring, observing, testing or gauging the relevant characteristics of an item.

**Repair** – Physical action taken to restore the required function of the faulty item.

(Source of definitions is EN 13 306: 2001, Maintenance Terminology)



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# LIST OF ABBREVIATIONS

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CMMS - Computerised Maintenance Management System

RCM - Reliability Centred Maintenance

PM - Preventive Maintenance

MTTF - Mean time to failure

CM - Corrective Maintenance

MTBF - Mean time before failure

MTTR - Mean time to repair

KPI - Key Performance Indicator

MPI - Maintenance Performance Indicator

CBM - Condition Based Maintenance

LHD - Load Haul Dump

TPM - Total Productive Maintenance

PDM - Predictive Maintenance



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# 1. INTRODUCTION

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*This chapter gives a brief description of the information contained in this research which include background of the maintenance management approaches evolution, it also contain a brief discussion of the objectives, significance of the study as well as limitation of the research.*

## 1.1 Background

Each year around the world billions of dollars are spent on equipment maintenance, and since the industrial revolution, maintenance of engineering equipments has been a real challenging issue. Over the years remarkable progress has been made in maintaining engineering equipment in the field, but it has still remained a challenge due to factors such as complexity, size, competition, cost, and safety (Unger et al., 1994). Also the increase in mechanization, automation and amalgamation of processes within the mines has further complicated the issue of maintenance (Kumar, 1996). In regard to cost, past experience shows that mining equipment maintenance costs range from around 20% to over 35% of total mine operating costs and are increasing steadily (Unger et al., 1994). To control these costs, mining companies have centred their efforts on areas such as optimizing scheduled maintenance operations, deferring nonessential maintenance, reducing maintenance manpower, controlling inventories of spare parts more effectively, and using contract maintenance support (Unger et al., 1994). In general the companies have centred their effort in better and proper maintenance procedures and practices for their mobile equipments. The challenge is more visible in the environments such as underground mining operations where practical control of the maintenance cost needs dedication on implementation of effective way of maintenance planning and procedures in place. It is important that underground mining management are aware of effective workable maintenance planning and that failure to do so results into management inability to know their needs. It is possible to implement a successful maintenance planning system as long as systems and procedures are formally developed and implemented to provide a logical, disciplined approach to maintenance. Better control of maintenance organization in terms of team work, proper and timely accomplishment of the tasks such as data recording and reporting also plays a major role during implementation of successful maintenance planning system.

## 1.2 Statement of the problem

In the thesis, the author's opinion is that, equipments availability and reliability in today's mining business needs special attention in order to reduce operational cost and capital cost so as to attain optimum profitability. In many underground mines, mobile mining equipments are the most critical units in the mine production systems. Drill rigs for development and production, vehicles for charging holes, LHD's for loading and transportation, scaling rigs and rigs for reinforcement and cable bolting are all important units in the process to generate a continuous ore flow. High and controllable reliability are also an important issue especially for all attempts to automate production equipment.

## 1.3 Objectives

- To determine major causes of equipment breakdown.
- To identify existing maintenance problems and suggest measures for improvements.

- Evaluate the existing CMMS and suggest measures for improvement.

## **1.4 Significance of the study**

The study will help the underground mine companies regarding mobile equipment to discover existing equipments breakdown and maintenance problems so that required action can be taken to improve the situation.

## **1.5 Scope of work**

- The research is limited to issues related to maintenance procedures and practices for mobile underground mining equipments, specifically LHDs in the case study mines.
- Analysis of CMMS is limited to the applications of the system which is the way data are handled and communicated throughout the case study mines.

## **1.6 Thesis layout**

Chapter 1; an introduction part; gives the background of the research and discusses best maintenance practices, contains a brief discussion of research objectives, significance of the study and scope of work.

Chapter 2; provides a description of research methodology used to build up results, technique and strategies.

Chapter 3; based on literature survey, includes an overview of underground mobile mining equipments maintenance practices and provides a background to maintenance management approaches and strategies.

Chapter 4; contains the case study data analysis and also present results obtained from discussions. The results are compared with the maintenance best practices.

Chapter 5; contains discussion of the results, conclusion derived and recommendations, as well as a suggestion for possible future research work.

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## 2. METHODOLOGY

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*This chapter provides a description and explanation of the research background as well as the approach (plan and method) that was used to build up the results of the project.*

### **2.1 Research background**

Achieving high standard of maintenance procedures and practices for underground mobile mining equipments is very essential in the current world of high degree of business competitions, high technology advancements and strictly environmental laws and policy. This research is industrial based, and aimed at identifying major sources of equipment breakdowns and existing maintenance problems including CMMS evaluation. Two case studies are presented and discussed; the case studies are LKAB-Malmberget mine in Sweden and Barrick Gold Tulawaka mine in Tanzania. These underground mines perform their operations with the idea of continuous improvement on equipments maintenance; both mines have their maintenance philosophy based on better maintenance performance. The plan is to frequently improve their maintenance management systems especially CMMS to ensure better equipments availability and reliability. Data were collected through document studies, questionnaire and oral interviews with workers (stakeholders); data were analysed in the time scale of this project.

### **2.2 Research Approach**

Different research problems have different systematic approaches to solve them. In this research, two case studies in underground mines have been discussed and analysed based on qualitative and quantitative research approaches as the data which have been collected are both quantitative and qualitative in nature. To have an in-depth understanding of the research types as well as qualitative and quantitative research background here under is a useful discussion.

Table 2:1 Summary of the types of research (Sridhar, 2008).

<p><b>Descriptive/Survey(Ex-post facto)</b>          Surveys and fact finding inquiries          No control over variables          Try to discover causes (i.e. ex-post facto)</p>	<p><b>Analytical</b>          Uses facts or information already available and analysis to make critical evaluation</p>
<p><b>Applied research</b>          Finding a solution for an immediate problem and not rigorous/flexible in application of the conditions</p>	<p><b>Fundamental (basic or pure) research</b>          Concerns with generalization and formulation of theory.          Knowledge for knowledge's sake ( i.e. pure or basic research)</p>
<p><b>Quantitative research</b>          Measured and expressed in terms of quantity.          Expression of a property or quantity in numerical terms.          Quantitative research helps:          a. Precise measurements          b. Knowing trends or changes overtime          c. Comparing trends or individual units</p>	<p><b>Qualitative research</b>          Involves quality or kind.          Helps in having insight into problem or cases.          Involves smaller number of participants</p>
<p><b>Conceptual</b>          Related to some abstract idea or theory (for thinkers and philosophers).          Relies on literature.</p>	<p><b>Empirical</b>          Relies on experience or observation alone, i.e. data based research          Capable of being verified by observation or experiments          Experimenter has control over variables.</p>
<p><b>Other types</b></p> <ul style="list-style-type: none"> <li>▪ One time or Cross sectional vs. Longitudinal/Development and trend</li> <li>▪ Field setting vs. Laboratory/Simulation research</li> <li>▪ Clinical vs. diagnostic studies</li> <li>▪ Exploratory vs. Formulated (the degree of formulation of the problem) studies</li> <li>▪ Historical studies</li> <li>▪ Correlation research</li> <li>▪ Conclusion orientated or decision orientated research</li> </ul>	

### 2.2.1 Quantitative research

Quantitative research is generally associated with the positivist/post positivist paradigm. It usually involves collecting and converting data into numerical form so that statistical calculations can be made and conclusions drawn. Researchers normally have one or more hypotheses. These are the questions that they want to address which include predictions about possible relationships between the things they want to investigate (variables).

Objectivity is very important in quantitative research. The main emphasis of quantitative research is on deductive reasoning which tends to move from the general to the specific. This is sometimes referred to as a top down approach. The validity of conclusions is shown to be dependent on one or more premises (prior statements, findings or conditions) being valid. (Georges, 2009)

### **2.2.2 Qualitative research**

Georges (2009) describes qualitative research as the approach that usually associated with the social constructivist paradigm which emphasises the socially constructed nature of reality. It is about recording, analysing and attempting to uncover the deeper meaning and significance of human behaviour and experience, including contradictory beliefs, behaviours and emotions. Moreover the approach adopted by qualitative researchers tends to be inductive which means that a theory is developed or look for a pattern of meaning on the basis of the data that collected. This involves a move from the specific to the general and is sometimes called a bottom-up approach (Georges, 2009). Data is collected in textual form on the basis of observation and interaction with the participants e.g. through participant observation, in-depth interviews and focus groups. It is not converted into numerical form and is not statistically analysed. Principally the method need to use methods which give participants a certain degree of freedom and permit spontaneity rather than forcing them to select from a set of pre-determined responses (of which none might be appropriate or accurately describe the participant's thoughts, feelings, attitudes or behaviour) and to try to create the right atmosphere to enable people to express themselves (Georges, 2009). Sampling strategies of the research is usually collected from small, purposeful, non-random samples that are information rich (Merriam, 1998), this may be because the methods used such as in-depth interviews are time and labour intensive but also because a large number of people are not needed for the purposes of statistical analysis or to make generalizations from the results. These two approaches can be used in the same study (Georges, 2009).

It should be noted that, this research aims not at drawing any statistical generalisations, but at gaining a deeper understanding of how maintenance procedures and practices for underground mining equipment may be characterised.

## **2.3 Research method/strategy**

Case studies as a research method or strategy have traditionally been viewed as lacking rigour and objectivity when compared with other social research methods. This is one of the major reasons for being extra careful to articulate research design, and implementation. On the other hand, despite this scepticism about case studies, they are widely used because they may offer insights that might not be achieved with other approaches. Case studies have often been useful tool for the preliminary, exploratory stage of a research project, as a basis for the development of the 'more structured' tools that are necessary in surveys and experiments. (Rowley, 2002)

Yin (1994) p.13 defines case study research as follows:

*"A case study is an empirical inquiry that:*

- *Investigates a contemporary phenomena within its real life context, especially when*
- *The boundaries between phenomenon and context are not clearly evident."*

The good thing with the case study is its encouragement to integrate different sources, research strategies and data types throughout the research work. As it has been explained previously, this research involves two case studies from underground mines whereby quantitative and qualitative data were collected and analysed. The general flow plan of the methodology is visualized in Figure 2:1, which gives an understanding on how the method suits the stated objectives.

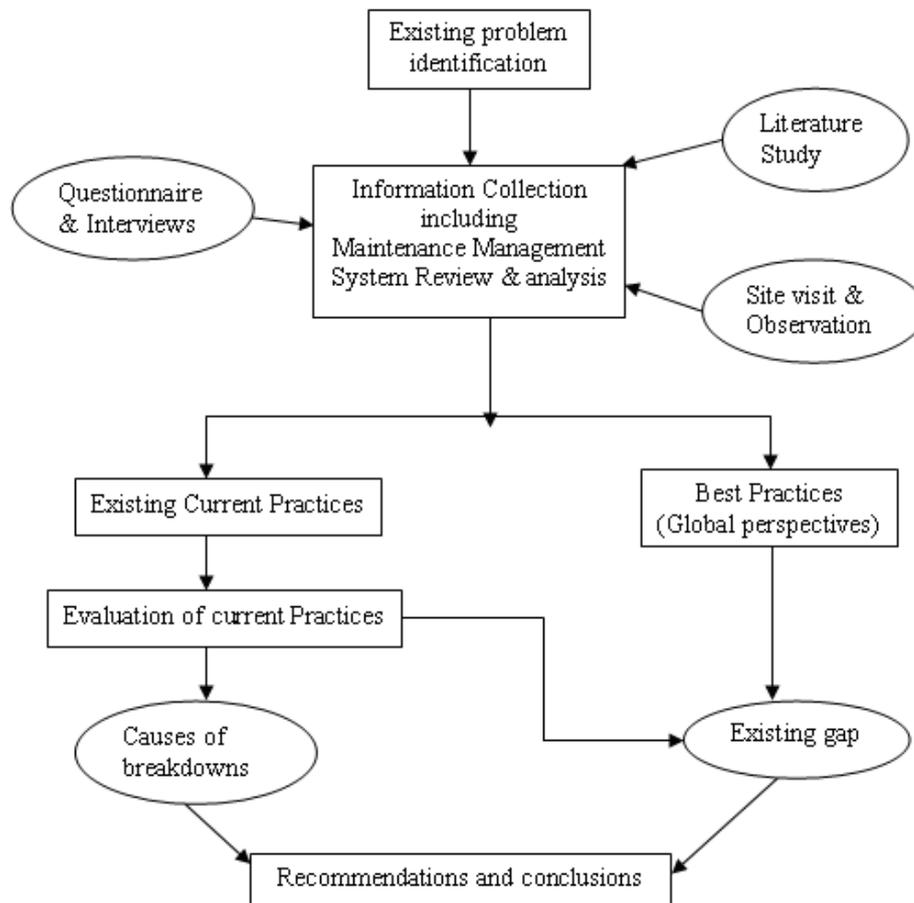


Figure 2:1 Flow plan of the methodology for this research according to researcher.

Data was collection with the use of surveys, interviews, questionnaires, observations, and document studies. With regards to questionnaire design, the interview questions covered a good range of maintenance department staff levels, from maintenance managers to shop floor workers. The discussions and questions were specific to the area of operation of a staff member in question. The current existing maintenance practices was explored, evaluation have been done in order to identify the major causes of equipment breakdown and also to identify the gap existing between the current maintenance procedures and practices in the mine with the best world class benchmarks maintenance practices based on the literature study.

## 2.4 Data gathering

Data collection plays an important role in a research study of any kind. The impact of incorrect data collection can cause the results of the whole research study to be illogical. The scale of data collection methods is very wide ranging from quantitative methods to qualitative methods. Table 2:2 describes some important data collection methods as proposed by Archer, T. (1988).

Table 2:2 Description of some important data collection methods by Archer, T. (1988).

<b>Data Collection Method</b>	<b>Descriptions</b>
Behaviour Observation Checklist	A list of behaviours or actions among participants being observed. A tally is kept for each behaviour or action observed.
Knowledge Tests	Information about what a person already knows or has learned.
Opinion Surveys	An assessment of how a person or group feels about a particular issue.
Performance tests	Testing the ability to perform or master a particular skill
Delphi Technique	A method of survey research that requires surveying the same group of respondents repeatedly on the same issue in order to reach a consensus
Q-sorts	A rank order procedure for sorting groups of objects. Participants sort cards that represent a particular topic into different piles that represent points along a continuum.
Self-Ratings	A method used by participants to rank their own performance, knowledge, or attitudes.
Questionnaire	a group of questions that people respond to verbally or in writing
Time Series	measuring a single variable consistently over time, i.e. daily, weekly, monthly, annually
Case Studies	experiences and characteristics of selected persons involved with a project
Individual Interviews	Individual's responses, opinions, and views
Group Interviews	small groups' responses, opinions, and views
Wear and Tear	measuring the apparent wear or accumulation on physical objects, such as a display or exhibit
Physical Evidence	residues or other physical by-products are observed
Panels, Hearings	opinions and ideas
Records	information from records, files, or receipts
Logs, Journals	a person's behaviour and reactions recorded as a narrative
Simulations	a person's behaviour in simulated settings
Advisory, Advocate Teams	ideas and viewpoints of selected persons
Judicial Review	Evidence about activities is weighed and assessed by a jury of professionals.

After choosing the data gathering method that fits the research, some important issues need to be given attention. Table 2:3 below is a summary of some issues to remember when choosing data collection methods according to Brinkerhoff .R et al., (1983).

Table 2:3 Explanation of issues to remember when choosing data collection method (Brinkerhoff .R et al., 1983).

<b>Issue to remember</b>	<b>Explanation</b>
Availability	Information may be already available that can help answer some questions or guide the development of new guidelines. Review information in prior records, reports, and summaries.
Need for Training or Expert Assistance	Some information collection methods will require special skill on the part of the evaluator, or perhaps staff will need to be trained to assist with the evaluation.
Pilot Testing	Researcher will need to test the information collection instrument or designed process, no matter the form or structure. There is a need to plan time for this step and for any revisions that may result from this testing.
Interruption Potential	The more disruptive an evaluation is to the routine of the project, the more likely that it will be unreliable or possibly sabotaged by those who feel they have more important things to do.
Protocol Needs	In many situations, researcher needs to obtain appropriate permission or clearance to collect information from people or other sources. Researcher has to allow time to work through the proper channels.
Reactivity	The ways which have been used to ask something should not alter the response. Reactivity may also be a concern and possibly alter the results.
Bias	Bias means to be prejudiced in opinion or judgment. Bias can enter the evaluation process in a variety of ways. For example, if self-selected sample is used (when a person decides to participate in a study, rather than being picked randomly by the researcher).
Reliability	Evaluation process designed needs to consistently measure what was intended to measure. If multiple interviews have been used, settings, or observers, need to consistently measure the same thing each time. If instrument has been designed, people have to interpret questions the same way each time.
Validity	The information collection methods designed needs to produce information that measures what is supposed to be measured. It is important to be sure that the information collected is relevant to the evaluation questions intended to be answered.

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## 3. LITERATURE SURVEY

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*This chapter gives detailed description of different underground mobile mining equipment maintenance procedures and practices and provides a background to maintenance management approaches and strategies; in addition the world class mobile mining equipment maintenance practices are discussed.*

### 3.1 Maintenance in mining environments

Maintenance is a combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function (EN 13 306, 2001). Proper maintenance and repair are very crucial for any kind of equipment which is subjected to operations. Safety assurance also is an important parameter to be taken care of when dealing with operational business entity, it is even more critical when operations are associated with underground mining production systems due to its environment and space limitations. To improve safety and production capacity in mining, knowledge of maintenance strategies is needed, and this knowledge should have its base in the areas of interacting factors to maintenance. Watson (1968) presents some of the critical interacting factors which influences a mine production system's reliability.

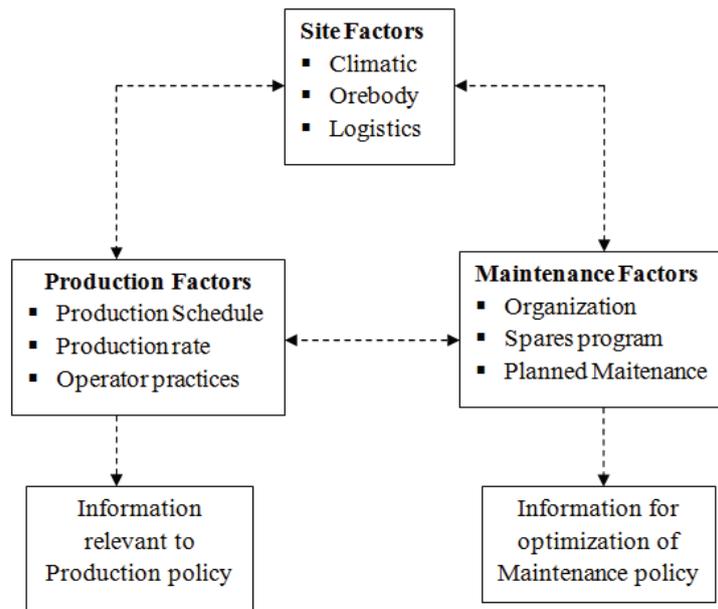


Figure 3:1 Factors affecting Maintenance Strategies (Watson, 1968)

If these interacting factors can be managed properly it is obvious that equipments reliability will be improved readily, reduction of operational cost and profit maximization will be the end results (Watson, 1968).

### 3.2 Maintenance types and strategies

According to EN 13 306 (2001) standards, maintenance practices approaches can be grouped into two major groups, namely Preventive Maintenance (PM) and Corrective Maintenance (CM) (Figure 3:2). Preventive approach can further be subdivided into condition based maintenance and predetermined maintenance; this implies that PM can be time based or condition based. Corrective maintenance has been subdivided into two subgroups which

are deferred and immediate; CM is an approach which is reactive in nature as compared to PM which is a proactive form of maintenance. Timing plays a major role in all these approaches (Smith, 2002). Researcher's view is that if a business entity such as an underground mining equipment maintenance department best fit in maintenance strategy will experience cost saving.

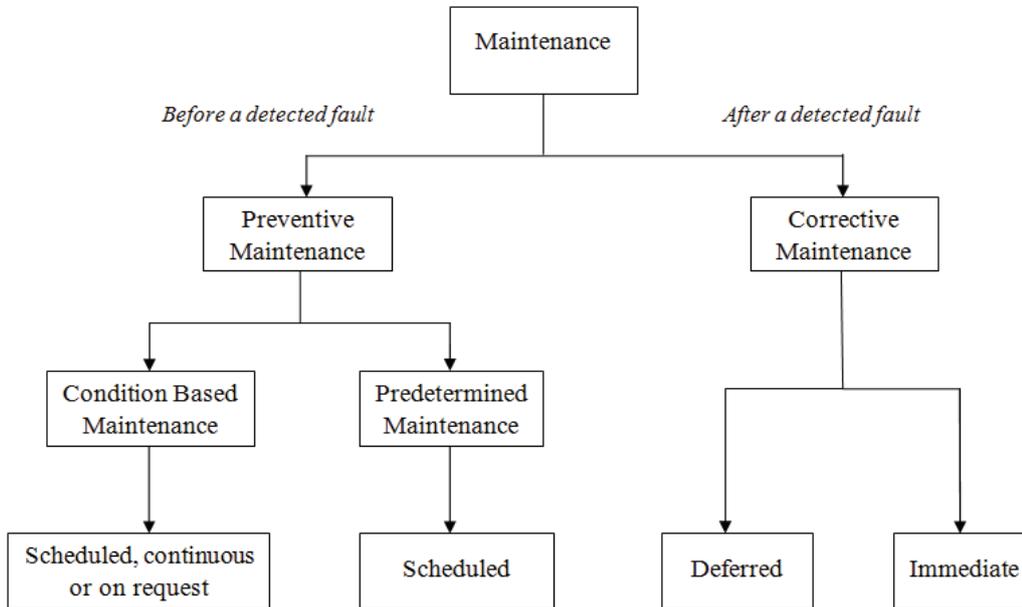


Figure 3:2 Maintenance overview chart according to EN 13 306 (2001)

### 3.2.1 Corrective Maintenance (CM)

CM is the maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function (EN 13 306, 2001). This is the most expensive form of maintenance especially if the maintenance is going to be done urgently because no planning or coordination can be made. Therefore the start-up cost and the cost of lost production can be large (Kumar et al., 2010). CM does not involve forecasting of failure when an item tends to fail. Depending on the necessity of the failed item(s) on the functioning of the system, maintenance can be done immediately or deferred. CM is the maintenance strategy applied most often when it is difficult to predict when an item will fail.

### 3.2.2 Preventive Maintenance (PM)

PM is carried out at predetermined intervals or according to prescribed criteria and intend to reduce the probability of failure or the degradation of the functioning of an item (EN 13 306, 2001), all preventive management programs are time driven. The item to be maintained can either be replaced or reconditioned depending on the condition of an item. The failure rate of the item is its probability to fail over a given period of time. PM can be divided into condition based maintenance or predetermined maintenance (Coetzee, 2004).

### 3.2.3 Condition Based Maintenance (CBM)

According to EN 13306, (2001) CBM of an item is PM based on performance and/or parameter monitoring and the subsequent actions. The standard needs to take note that performance and parameter monitoring may be scheduled, on request or continuous. Condition monitoring and inspection are the two main strategically approaches to CBM of

an item. In condition monitoring, parameters are measured to ensure that maintenance is done before failure and is performed based on predetermined criteria. Inspection is done at regular intervals by a person involved in maintenance to ensure that maintenance is performed as soon as it is required. Through regular inspections, measurements or tests, or continuous monitoring, one can determine when it is time for replacement, servicing or adjustments. These checks can be performed in three ways:

- Using the subjective senses (sight, hearing, touch, smell and taste)
- Intermittent or continuous use testing methods for detecting wear
- Running the equipment and notice that all functions work (Kumar et al., 2010).

Coetzee, (2004) identified that CBM is normally suitable when failure rate is dependent on operating condition rather than time.

A complete CBM program must include monitoring and diagnostic techniques. These techniques include vibration monitoring, acoustic analysis, motor analysis technique, motor operated valve testing, thermography, tribology, process parameter monitoring, visual inspections and other non-destructive testing techniques. Explanations for some of the commonly used CBM techniques according to Mobley, 2002 is here under.

### ***Vibration Monitoring***

All mechanical equipments in motion generate a vibration profile, or signature that reflects its operating condition. This is true regardless of speed whether the mode of operation is rotation, reciprocation, or liner motion. Vibration analysis is applicable to all mechanical equipments; its profile analysis is a useful tool for predictive maintenance, diagnostics and many other uses.

### ***Tribology***

This is the general term that refers to design and operating dynamics of the bearing-lubrication-rotor support structure of machinery. Two primary techniques are being used for predictive maintenance; these techniques are lubricating oil analysis and wear particle analysis

### ***Lubricating oil analysis***

Lubricating oil analysis is an analysis technique that determines the condition of lubricating oils used in mechanical and electrical equipment.

### ***Wear particle analysis***

Wear particle analysis is related to oil analysis and the particles to be studied are collected by drawing a sample of lubricating oil. Whereas lubricating analysis determines the actual condition of the oil sample, wear particle analysis provide direct information about the wearing condition of the machine-train.

### ***Thermography***

Thermography can be used to monitor the condition of the plant machinery, structures and systems. It uses instrumentation design to monitor the emission of infrared energy (i.e., surface temperatures) to determine operating conditions.

### ***Ultrasonic***

Ultrasonic like vibration analysis is a sub set of noise analysis. The only difference in the two techniques is the frequency band they monitor. In the case of vibration analysis, the

monitored range is between 1Hz and 30,000Hz, ultrasonic monitor noise frequencies which are above 30,000Hz.

### 3.2.4 *Predetermined maintenance (PDM)*

Predetermined maintenance is carried out in accordance with established intervals of time or number of units of use but without previous condition investigation (EN 13 306, 2001). In order for PDM implementation to be successful, failure rate of an item needs to be increasing as the usage time of an item increases. Therefore the decision for the item maintenance interval should be based on machine hours, age, the frequency of use and the distance travelled (Coetzee, 2004). According to Mobley (2002) most groups of similar machines will display failure rates that can be predicted in some ways if averaged over a long period of time. The Bathtub curve (Figure 3:3) relates failure rate to operating time.

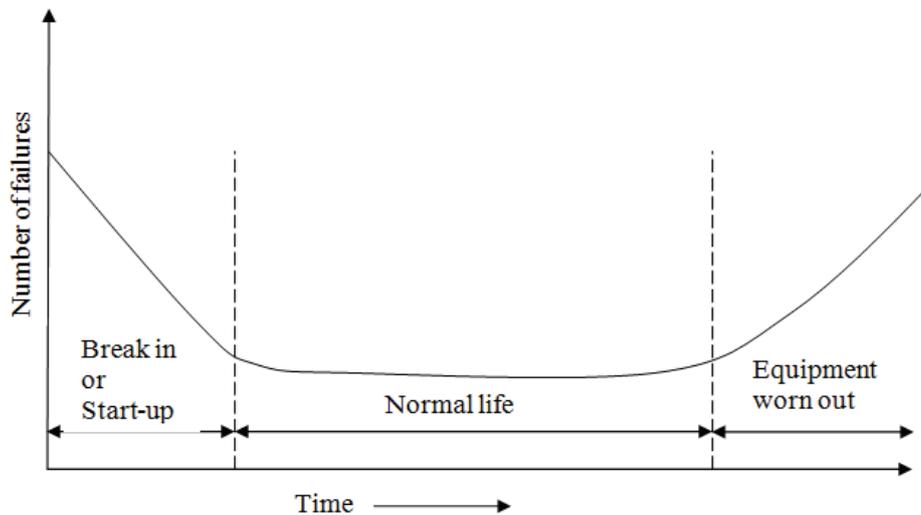


Figure 3:3 Typical bathtub curve (Mobley, 2002).

The mean-time to failure curve/Bathtub curve indicates that a new machine has a high probability of failure because of installation problems during the first few weeks of operation. After this initial period the probability of failure increases sharply with the elapsed time (Mobley, 2002).

### 3.2.5 *Total Productive Maintenance (TPM)*

TPM aims to maximise equipment effectiveness. It consists of a range of methods that are known from maintenance management experience to be effective in improving reliability, quality and production. TPM tries to improve a company through improving personnel and plant, and changing the corporate culture. Cultural change at a plant is a difficult task to perform and it involves working in small groups, a strong role for machine operators in the maintenance program, and support from the maintenance department (Willmott and McCarthy, 2000). In the TPM framework, the goals are to develop a "maintenance-free" design and to involve the participation of all employees to improve maintenance productivity. Original goal of total productive management is to "Continuously improve all operational conditions, within a production system; by stimulating the daily awareness of all employees" (Nakajima, 1988). Normally the company put forwards its main priorities based on its plans, and these priorities performance actions need to be measured, so the issue of the need of key performance indicators arise. The main parameters which usually are important

to measure are total system/plant effectiveness as well as system/plant productivity, availability, cost efficiency and quality (Moubray, 1997).

A metric, termed the “Overall equipment effectiveness (OEE)” is the benchmark used for world-class maintenance programs. The OEE is established by measuring equipment performance. Measuring equipment effectiveness must go beyond just availability or machine uptime. It must factor in all issues related to equipment performance. The formula for equipment effectiveness must look at the availability, the rate of performance and quality rate. This allows all departments to be involved in determining equipment effectiveness. The formula could be expressed as:

Availability x Performance Rate x Quality Rate = OEE. (Moubray, 1997)

### ***3.2.6 Reliability Centred Maintenance (RCM) and its application in mining***

The need for effective and efficient maintenance management methods have resulted into the development of RCM (Nowlan and Heap, 1978). RCM is a process used to determine what must be done to ensure that any physical asset continues to do what its users want it to do in its present operating context (Moubray, 1997), the process was developed within the aircraft industry and later adopted to several other industries and military branches. A high number of standards and guidelines have been issued where the RCM methodology is tailored to different application areas. The major advantage of the RCM analysis process is that, it is a structured and traceable approach to determine the optimal type of PM (Rausand and Vatn, 2006). This is achieved through detailed analysis of failure modes and failure causes. Although the main objective of RCM is to determine the preventive maintenance, the results from the analysis may also be used in relation to corrective maintenance strategies, spare parts optimization and logistic consideration; in addition, RCM has an important role in overall system safety management (Rausand and Vatn, 2006). The use of RCM in mining industry is very minimal, however some of the mines have implemented the method carefully with successful results, for example Hammersley (Open pit Mine) in Australia (Knowles, 1994). The fact that RCM can handle complex system operations with optimal results makes it attractive technique to be used in Mining industries to optimize their maintenance activities.

### ***3.2.7 Computerised Maintenance Management Systems (CMMS) and its benefits***

CMMS is also known as Enterprise Asset Management and Computerized Maintenance Management Information System (CMMIS). A CMMS software package maintains a computer database of information about an organization’s maintenance operations, i.e. CMMIS - computerized maintenance management information system. The software has evolved from relatively simple mainframe planning of maintenance activity to window based, multi-user systems that cover a multitude of maintenance functions. The capacity of CMMS to handle vast quantities of data purposefully has rapidly opened new opportunities for maintenance, facilitating a more deliberate and considered approach to managing assets (CMMS, 2011). Among others, the greatest benefit of the CMMS is the elimination of paperwork and manual tracking of activities, thus enabling the staff to become more productive. It should be noted that the functionality of a CMMS lies in its ability to collect and store information in an easily retrievable format (Sullivan et al., 2004). A CMMS does

not make decisions; rather it provides the Operational & Management manager with the best information to affect the operational efficiency of a facility.

Benefits with having a CMMS include the following:

- Detection of impending problems before a failure occurs resulting in fewer failures and customer complaints.
- Achieving a higher level of planned maintenance activities that enables a more efficient use of staff resources
- Affecting inventory control enabling better spare parts forecasting to eliminate shortages and minimize existing inventory.
- Maintaining optimal equipment performance that reduces downtime and results in longer equipment life (Sullivan et al., 2004).

CMMS is widely used as a method of controlling group industrial maintenance operations. Many industries have learned that CMMS software can be most beneficial in virtually every type of group industrial maintenance setting (Software-directory, 2011). According to software-directory (2011), the CMMS market is quite large and active due to a fast return on investment realized when CMMS is implemented with diligence. CMMS Software packages range widely in both breadth and cost. Finding the best CMMS for a business can be challenging. Here under are some of the most popular used CMMS in open pit and underground mines (software-directory, 2011)

Maintenance Connection: it has a full-featured web-based maintenance management which includes work order tracking, PM, PdM, asset management, built-in procedure libraries, inventory tracking, purchasing, scheduling, and service requests.

MicroMain: has open-source maintenance management solution including automated Work orders, PM scheduling, maintenance alerts, asset tracking and history, wireless inventory control, fleet management, and enterprise-level reporting.

EMaint X3 EAM/CMMS: Used to schedule and plan maintenance, track all work orders and work requests, control inventory, equipment downtime and system administration costs.

Modular Mining System INTELLIMINE: Uses wireless communication subsystem to control maintenance processes.

MAPCON CMMS Software: designed to fit different sized operations. It is a full-featured work order and PM software systems integrating asset management, inventory and purchasing.

### **3.3 Failure causes for an engineering system**

It is important to have a good understanding about the issues that can cause an engineering system or component to fail. According to Naikan (2009), failure of a system or component is the inability of a system or component to deliver its intended function satisfactorily, it may be either partial or complete. It is essential for any reliability system to start with a clear and objective definition of failures, preferably in quantitative terms to avoid any confusion at some stage. There are many causes of failures for components and systems. Some of these are known and others are unknown due to many reasons. Whatever the mechanisms and causes of failures, it results in either decreasing the strength of the component or increasing the applied load on it or both simultaneously. When this occurs the component fails at a point

when the load on it exceeds its strength. A comprehensive list and details of some causes of system failures and unreliability are shown in Table 3:1.

Table 3:1 Causes of failures of engineering components and systems by Naikan (2009)

<b>Causes of failure</b>	<b>Details</b>
Poor design	Wrong materials, wrong dimensions and tolerances, improper design models without considering the load and its fluctuations, stress concentration, inadequate interface design, lack of process design, no interchangeability of parts
Incorrect manufacturing	Usage of outdated technology and old machines, lack of control over the process, usage of wrong tools, lack of calibrated instruments, inadequate training
Improper testing	Wrong methods of testing, improper burn-in, inadequate data management, usage of improper model for quantification
Complexity	More number of components and interconnections, more number of interfaces
Improper maintenance	Under- and over- maintenance, wrong tools and methods, non-interchangeable spare parts, poor spare parts management
Raw material supply	Poor vendor evaluation and inadequate screening of materials, lack of understanding and agreements on suppliers.
Quality assurance	Low process capability of machines, in adequate quality control, inadequate instruments and training, wrong sampling techniques
Packaging, shipping, transportation	Road, rail, air, water transportation requires special packaging with shock resistance and environmental protection. Lack of this damage the system during transportation
Improper installation	Improper foundation, excessive vibration, inadequate inputs (Voltage, current etc), bad quality accessories, usage of wrong tools and methods
Operational instruction	Wrong instruction, lack of clarity, difficult to understand, poor language of manual
Human error	Lack of understanding of process and equipment, carelessness, forgetfulness, poor judgemental skill, physical disability and fatigue

Dealing with maintenance practices especially in underground mining environments where safety has to be given high attention, needs careful means for data recoding and management. This can be done efficiently through the use of statistical approaches. Mueller, (1995), emphasised the application of statistics in analysing maintenance data in the mining industry as it normally leads to opportunities for cost reduction. It is clear that replacing a component before it fails (preventively) may, under certain circumstances, make better economic sense than replacing the component when it fails (correctively), (Reliasoft, 2000). It can be seen that the corrective replacement costs increase as the operating time interval increases (Figure 3:4). In other words, the less often you perform a PM action, the higher your corrective costs will be. Obviously, the longer we let a component operate, its failure rate increases to a point that it is more likely to fail, thus requiring more corrective actions. The opposite is true

for the preventive replacement costs. The longer you wait to perform a PM, the less the costs; while if you do PM too often, the higher the costs. If we combine both costs, we can see that there is an optimum point that minimizes the costs. In other words, one must strike a balance between the risk (costs) associated with a failure while maximizing the time between PM actions (Reliasoft Cooperation, 2007).

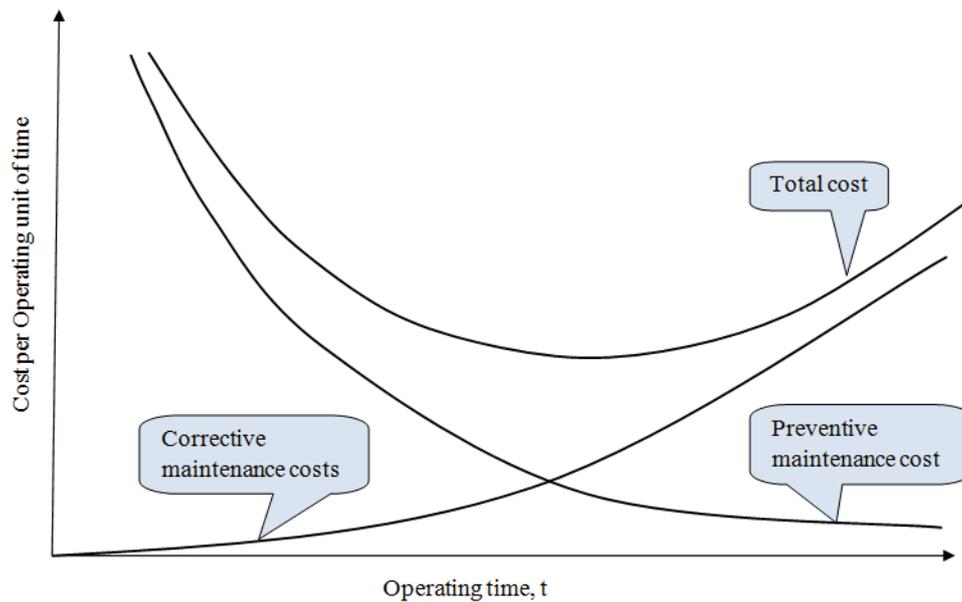


Figure 3:4 Cost per operating unit time vs. operating time (Reliability Edge, 2000)

### 3.4 Maintenance Management

Like in any other area of technology, management plays an important role in maintenance activity. Procedures and strategy are normally derived from maintenance management for all maintenance-related activities in addition to exercising required management and technical control of maintenance programs.

Management surveys show that the average productivity of maintenance employee is between 25 to 35% (Wireman, 1994). This means that a craftsman has less than 3 hours of productive time per 8hour shift, due to poor maintenance management (Wireman, 1994). It is normally important that the manufacturing or production companies identify, define and communicate the maintenance strategies as business strategies are communicated to other business companies. With connection to the maintenance practises and procedures, Vanneste and Vassenhove, (1995) proposed that, maintenance management process has two parts; the first one is Effectiveness analysis which mainly deals with detecting the most important problems and potential solutions and the second is efficiency analysis which deals with identification of the suitable procedures. Eight phases are defined, namely; determination of existing performance of the plant/machine, downtime and quality problem analysis, effectiveness analysis of the alternative solutions, efficiency analysis of maintenance procedures, plan actions, data collection and implementation actions, data processing and actions monitoring, and the last one is to adapt plans or information procedures in case of undesired deviations.

### 3.5 Maintenance Performance

An organization always can spend considerable resources and time for measuring the performance and to assess the success of the organization (Parida, 2007). Performance measurement literature emphasizes the importance of maintaining relevant measures that continue to reflect the issues of importance to the business (Lynch and Cross, 1991). However, most of the organizations pay little or no attention to integrating the performance measurement system with their organizational hierarchical levels and the different measurement criteria linked to the external and internal stakeholders as well as the operational process (Parida, 2007). In addition, not enough importance is given to the external and internal effectiveness to achieve total maintenance effectiveness for the organization, (Parida, 2007). To be able to measure and improve performance of a process there should be existing current performance as a benchmark, so a set of equations and various types of approaches are involved in measuring the effectiveness and efficiency of the maintenance performance in the organization with the main aim of persuade maintenance staff to think of appropriate maintenance improvement strategies over the past experienced one. Some important maintenance performance indicators are availability, reliability, process rate and maintainability. EN 13 306, (2001) defines availability as an ability of an item to be in a state to perform a required function under given conditions at a given instant of time or during a given time interval, assuming that the required external resources are provided. Many mines use key performance indicators such as availability and production in order to evaluate the performance of the maintenance and operation groups (Lewis, 2001).

$$\text{Availability} = \frac{\text{Scheduled operating time} - \text{Downtime}}{\text{Scheduled operating time}}$$

The measure is independent of the cause of the downtime and merely gives the share of time which could be used by an item for its intended purpose. Availability gives the ratio between the actual operating time and the planned operating time (Nakajima, 1988). Other key indicators in mathematical expression are here under:

$$\text{Reliability} = (\text{Total production time}) / (\text{Number of failures})$$

$$\text{Process rate} = (\text{Ideal cycle time}) / \text{Actual cycle time}$$

$$\text{Maintainability} = (\text{Downtime due to failures}) / (\text{Number of failures})$$

$$\text{Equipment effectiveness} = \text{Availability} \times \text{process rate}$$

Source of equations is Campbell, (1995).

### 3.6 World class maintenance practices and benchmarking

Best maintenance practices are defined in two categories: standards and methods. Standards are the measurable performance levels of maintenance execution; methods and strategies must be practiced in order to meet the standards (Smith, 2002). The combination of standards with methods and strategies provides the elements of an integrated planned maintenance system. Achievement of the best maintenance practice standards (maintenance excellence) is accomplished through an interactive and integrated series of links with an array of methods and strategies (Smith, 2002). According to Wireman, (2003), best practices in maintenance are “the maintenance practices that enable a company to achieve a competitive advantage over its competitors in the maintenance process.” In other words the maintenance best

practices are the world class maintenance practices. Hiatt, (2009) suggested that in order to achieve the world class maintenance, the following steps have to be followed;

- Philosophical and theoretical shifts,
- Understanding change, teamwork and training,
- Asset management and warehouse/inventory control,
- Corrective maintenance (CM),
- Preventive maintenance (PM),
- Predictive maintenance (PdM),
- Purchasing, accountability and reliability centred maintenance (RCM).

The world class maintenance practices also needs continuous improvement in asset care of the ongoing process to make it sustainable. Benchmarking is one of the key tools for continuous improvement. To be able to benchmark successfully it is important to know the current status of the maintenance program and vision. Of the several types of benchmarking practices, one of the most successful is process benchmarking, which examines specific processes in maintenance, compares the processes to companies that have mastered those processes, and maps changes to improve the specific process (Campbell, 1995). The key to benchmarking is self-evaluation. Benchmarking is a very useful tool when it comes to regulatory compliance. Understanding how other companies achieve compliance can help companies modify their approach to achieve a higher level of compliance or reduce the current cost of compliance. By studying other companies' approaches, implementing improvements, and monitoring the improvements, increased compliance levels can be achieved (Wireman, 2003).

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## 4. CASE STUDIES

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*This chapter discusses mobile mining equipments maintenance procedures and practices for two underground mines (case studies), namely LKAB-Malmberget and Barrick Gold Tulawaka mine. Besides identifying major causes of equipments breakdown, the analysis for some equipment's PM and CM data has also been done and presented. In addition, mine maintenance procedures and practices comparison and benchmarking has been presented.*

### 4.1 Case study 1 – LKAB (Malmberget mine)

#### 4.1.1 Background to case study

LKAB's Malmberget mine is the second largest iron ore mine in Sweden. The mine is owned by Luossavaara-Kiirunavaara AB. It is located in Gällivare, 115km from Kiruna (Wikitravel, 2011) and contains some 20 orebodies spread over an underground area of about 5 by 2.5km. Seven orebodies are currently being exploited. Mining began in 1888, since when over 350Mt of ore have been won. LKAB employs around 1,000 people at Malmberget, of whom 900 work in mining, processing and administration (Net resources international, 2011). In 2009, Malmberget produced around 4.3Mt of pellets out of LKAB's total production of 17.7Mt of iron-ore products (Net resources international, 2011). Figure 4:1 shows where LKAB's Malmberget mine is situated.



Figure 4:1 Location of the Malmberget mine.

The scope of the discussion is underground mobile mining equipment, specifically in the area of its maintenance procedures and practices. For clear understanding of the Malmberget mine maintenance department and its activities discussion below has been presented.

#### 4.1.2 Available underground mobile equipments

Currently the mine has about fifty mobile equipment units including drill rigs, LHDs, scaling machine, charging trucks etc. When considering LHDs and drill rigs the mine has 13 LHDs with one being semi-automated and 6 drill rigs which are all automated. The focus of this

case study is the LHD operations. To have an overview of the existing LHDs (Table 4:1), the description of the machine stating its identity, quantity, manufacturer, the year which machine was brought for work and its capacity is shown.

*Table 4:1 Details of the LHDs available in the mine*

<b>Equipment type (ID)</b>	<b>Capacity(ton)</b>	<b>Manufacturer</b>	<b>Year</b>
T67-Toro 0011	21	Sandvik	2005
T68-Toro 0011	21	Sandvik	2005
T69-Toro 0011	21	Sandvik	2005
T71-Toro 010	21	Sandvik	2002
T76-Toro 650	21	Sandvik	2002
T78-Toro 010	21	Sandvik	2002
C3-Cat/E	21	Caterpillar	2005
C4-Cat/E	21	Caterpillar	2005
C5-Cat/E	21	Caterpillar	2003
C6-Cat/E	21	Caterpillar	2003
C7-Cat/E	21	Caterpillar	2003
C8-Cat/E	21	Caterpillar	2000
C9-Cat/E	21	Caterpillar	2005

### **4.1.3 Organization chart and the Maintenance workforce**

The total maintenance team sums up to 60 workers, among them 2 are female. In addition 8 employees are in high managerial level. Figure 4:2 represent organization charts for the company and maintenance department of LKAB Malmberget mine.

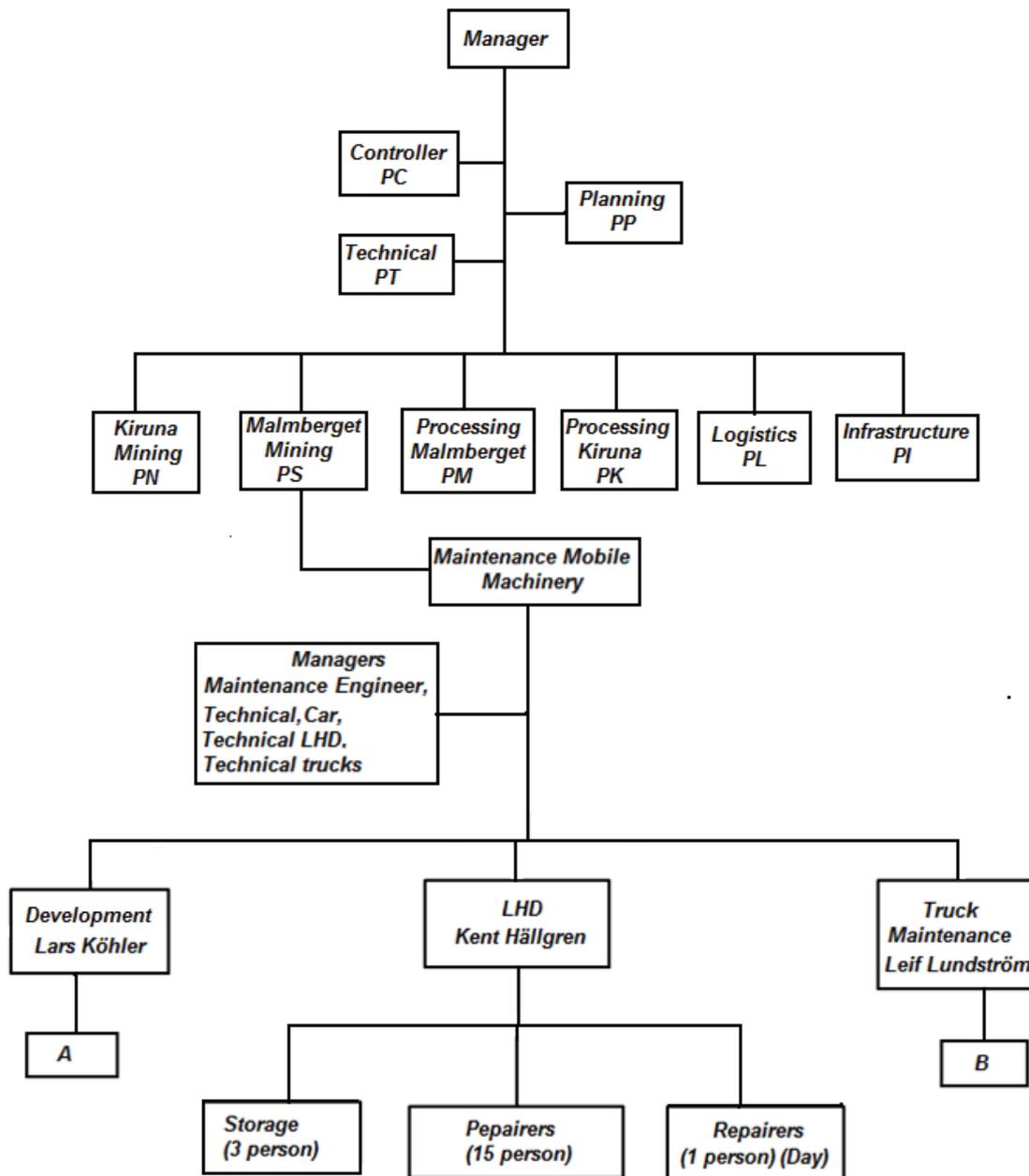


Figure 4:2 Flow chart showing the overall LKAB and maintenance department (Malmberget mine) organization structure 2011.

Figure 4:2 show the overall organization structure of LKAB whereby Kiruna mine is included, it also includes among other divisions, processing plants in both Kiruna and Malmberget. It can be seen that the maintenance mobile machinery department at Malmberget mine consist of technical managers as well as subdivisions for LHDs, Development equipment, and trucks maintenance. A and B represents some more subdivisions of development and truck maintenance which is out of scope of this research.

#### 4.1.4 Results and analysis

As it was not possible to interview all department members, the key personnel who are responsible for the maintenance department activities were selected, the selection process was based on the idea of making sure all levels of maintenance department processes were covered. In-depth and wide description of the maintenance procedures and practices which are performed at the department will be given. The discussions and interviews were done

with Maintenance manager, maintenance planner, maintenance supervisor as well as operators of the LHD machine and drill rigs. The questions for the conducted interview can be seen in appendix 1 and the results and summary of the interview and discussion are given in appendix 2. Below are the findings of the conducted interview and discussions, in addition data analysis are being presented in this part of the research.

**High production level achievement**

The main target of the production and maintenance department is to achieve optimum production under minimum or no obstruction. The maintenance planner gives the input which makes the production manager and repairmen to manage the game plan of 9 LHDs available at all times. The maintenance planner also plans the repairs and makes sure that all spare parts are available when needed. To achieve availability of spare parts at all times is not easy. In some cases too much time is spent with corrective maintenance due to waiting for spare parts arrival, as a result of the targeted number of 9 LHDs available at all times fails to be achieved. This consequently lowers the production capacity.

**Maintenance activities programs**

The department has 3 shifts which operates in the following time interval plan 06:00 – 14:24, 13:36 – 22:00 and 15:36-24:00 (for the last shift, weekends are off working days). Each shift has a group of 5 persons with the duties listed in Table 4:2.

Table 4:2 Distribution of duties for a maintenance department shift working at the mine

No. of workers	Duties
1	Attending charging truck
1	Component repairs
1	Inspections
1	Repair hoses and pipes
1	Other works, flexible

The flow of maintenance work for LHDs at LKAB (Malmberget) can be categorized into PM Services and failure fixing/repair. The PM services is done every 250, 500, 1000, 2000 machine engine hours and an overall keen inspection takes place right after cleaning the machine to see what else should be maintained during service. Table 4:3 shows expected time for each service interval. In addition replacement for engine, converter, gearbox is done after every 13000-14000 machine hours while that of hydraulic pump and transmission system is done at 8000 and 10000 machine hours respectively.

Table 4:3 PM equipment service intervals with its expected time of completion

PM service interval (Machine hours)	Expected completion time (Hours)
250	3
500	8-12
1000	16
2000	32

To fix failures there is a service team in the field that makes sure the failure problem are fixed immediately, the work order for that job is normally written by service man or maintenance planner, and this is done under the budget allocated to the department. The total annual budget for maintenance is around 100MSEK, which covers all maintenance activities for all mobile equipments. The annual budget given for LHD maintenance is 40MSEK which corresponds to 40 percent of the total annual maintenance budget. However one interviewer suggested that this budget varies to fulfil proper execution of maintenance work processes at the mine.

### ***Underground workshop and services***

There are three workshops in the mine. The first one repairs drifts development vehicles (drill rigs, scaling machines, concrete trucks, trucks etc.); the second workshop maintains LHDs (Figure 4:3), scaling machines and big boulder trucks. The third workshop deals with maintenance trucks, mining trucks, fire trucks and busses. All these workshops are at level 815m, and deals with a wide range of maintenance services from major services to small repairs, bearing and brakes changing, transmission and motor changing. Some of the repair works which are conducted includes boom repair, bucket repair and equipment structural repair.



*Figure 4:3 Underground workshop at level 815m, to the left is the LHD in maintenance and to the right is the front side of LHD with its bucket being removed for repair.*

There is also an outsourced maintenance services within maintenance department, but this is done only for drilling activities which is not within the scope of this research work.

### ***Material/spare parts flow and storage room capability***

The mine has an underground storage room at level 815m (Figure 4:4), where most of the materials and spare parts are being stored. There are some other special underground storerooms for storage of big sized materials and spares such as tires and buckets. The mine also has a storage room which is shared with Kiruna mine. To facilitate and speed up the services, Caterpillar (manufacturer and equipment supplier) has its big storage room in Kiruna. As the maintenance supporting entities, storeroom/warehouse plays a role of ensuring proper and adequate inventory of parts to meet the mine's needs. The purchasing department buys all necessary consumables and takes care of all spare and material orders. Material/spare parts ordering and purchase procedures is done as follows, the work order is written by using Movex, a resource planning, scheduling and inventory control software. A service man or maintenance planner is the person responsible for writing the work order.

When the order is pressed, the manager has to approve and send it to purchase department who orders material. If the spare part or material requirement is urgently then calling and ordering the parts becomes the quick solution, when this happens the paper work normally comes later. The maintenance planner can also order material that are not available in the store or that seems to be running short. The storekeeper makes sure that the availability of spare tires, buckets and filters in the mine is constantly maintained, this is done since they are frequently being used for maintenance works. Caterpillar also allows other external companies to visit and buy materials and spare parts from their store room at the mine.



Figure 4:4 The underground storeroom shelves with material and spare parts (level 815m).

### ***Semi-automatic versus Manual LHDs operations***

Currently, mining production operations related to loading, hauling and dumping are conducted with LHD machines which are mainly operated by using manual mode of operation. The mine also has one semi automatic LHD machine which can be operated in either manual or semi-automatic mode. The maintenance management of this equipment still remain the challenge, as it involves human interactions with for example maintenance. In manual operation mode, the operator is fully involved to run the machine.

From the results of the interview and discussions operators prefer to operate in manual mode because of the following reasons;

*The need of better feelings of physical presence during operation*, if the operator drives the manual LHDs he/she gets a better feeling of the operations and its surroundings. It is not possible to notice the problems of the machine by human sense when driving semi-automated LHD also the status of the road (whether smooth or corrugated) can't be recognised.

*Underutilization of the machine when using semi automatic mode*, It becomes difficult to handle the loading process semi automatically when the material to be loaded contain big boulders, this may result into the machine underutilization.

*Communication problems during operation in semi automatic mode*, two way radio communication has been a problem in such a way that even when communication is down for a short while the machine stops and someone has to go down to machine to restart it. This can happen several times per shift leading to the loss of production time. The plan is to change the system to a modern one as the existing system was installed in 2007.

*Frequency of cleaning the path after operation in semi automatic mode*, when driving automated LHDs someone has to go to the drift/working area to clean the road after every shift.

*High speed operation achievement*, when driving in manual mode one can achieve more flexibility and speed, resulting into more loaded ton. The rear side of the semi automatic LHD is well designed (powerful lights and metal guards) to accommodate the incidents that may occur during operations such as wall hits during reversing. Figure 4:5 shows the different design models of the manual and semi automated LHDs.



Figure 4:5 The rear side of the manual LHD (left) and semi automated LHD (right)

The Figure 4:5 shows that the semi-automated LHD is properly designed to fit the underground environment with the operations in absence of human sense. More powerful lights and more protective guards have been added to the semi automated LHD to make the operations safer.

With all aforementioned facts discussed about operator’s preference of working with manual operating mode, it was also agreed that working with semi automated LHD is more safe as compared to manual especially in cases eruption of gases and fumes as well as risks of cave in and falling rocks, it also saves time as it becomes possible to work soon after blasting although when the machine stops because of the failure or breakdown someone has to attend it physically anyway. To have a deeper understanding of the manual and semi automatic operation comparisons for the LHDs C3 (machine identity refer Table 4:1) at the mine, quantitative data are provided and analysed here under. The loads carried in manual and semi automatic modes as well as the time taken to maintain the machine can be seen in Table 4:4.

Table 4:4 Comparison of loads and time taken for machine C3 to operate in manual and semi automatic modes from 2007 to 2010

Year	Machine operating hours	Auto mode operating hours	Manual mode operating hours	Loads auto mode (ktonnes)	Loads manual mode (ktonnes)	Maintenance time (Hrs)
2007	3078	1043	2035	276	713	920
2008	2981	461	2520	143	849	1191
2009	2342	866	1478	119	404	1861
2010	2160	806	1356	158	424	820

Figure 4:6 reveals that the manual operating mode of the machine dominates the time of operation as compared to semi automatic operation mode. In addition the load produced in manual operation mode was high as compared to the semi automatic mode of operation which is an obvious implication of the more dedication of time given to manual operating mode.

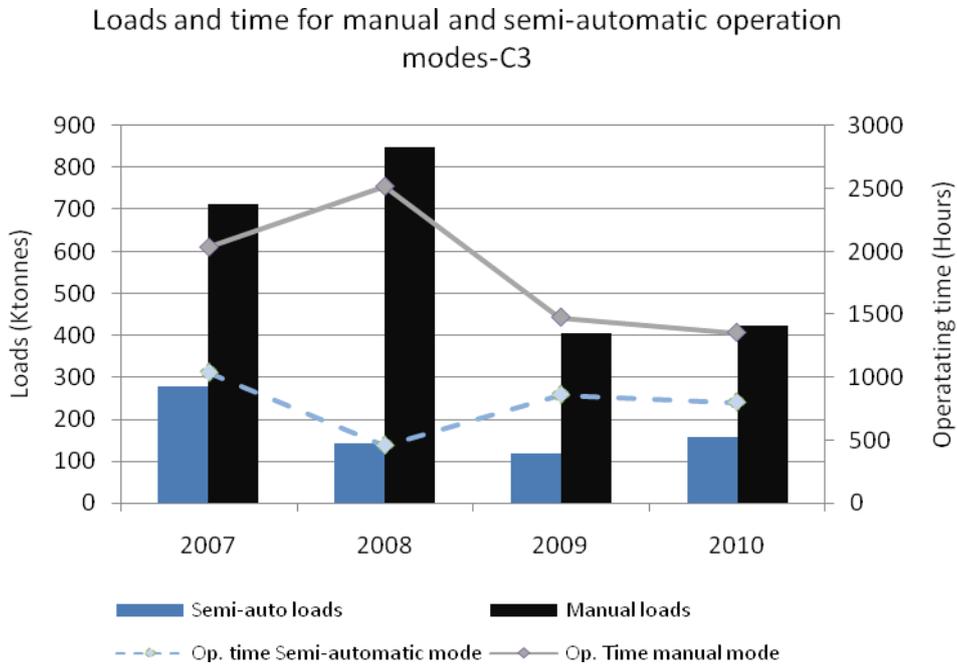


Figure 4:6 The comparison of the amount of loads produced by C3 in semi-automatic and manual operating modes with its corresponding times of operations.

Note that; In this thesis the names, machine C3, C4, to C9 represents different LHDs with their descriptions given in Table 4:1.

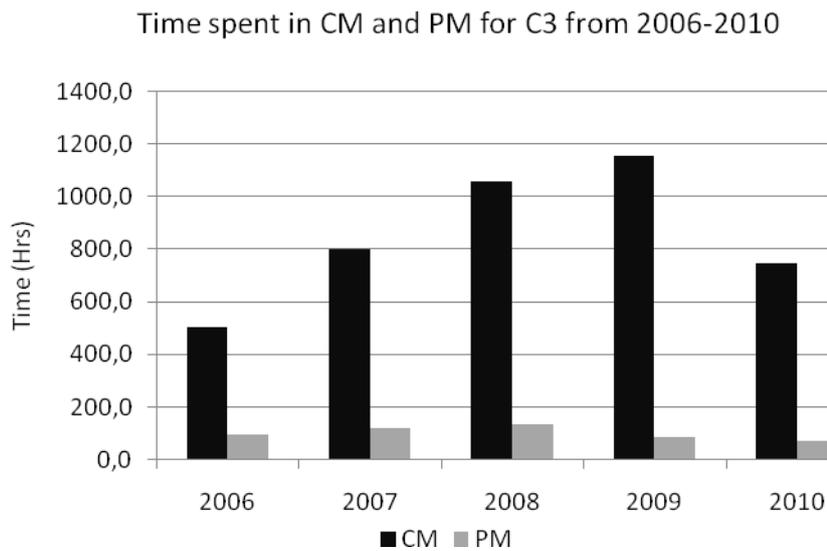


Figure 4:7 Time spent for CM and PM for machine C3 from 2006 to 2010

Analysis shows that, the Corrective Maintenance seems to dominate the maintenance activities at the department (Figure 4:7). The amount of time spent for CM was increasing each year in linear relationship indicating that proper planning , scheduling and control is required in order to immediately fix the problem of the machine, aging may also be another factor for the increase of CM. The decrease which occurs in 2010 is due to lack of CM and PM data from September to December.

***The key maintenance performance indicators***

The key performance indicators of the department are cost per ton (SEK/ton), Mean time to failure (MTTF) and equipment downtime. The person responsible for measuring these indicators is the maintenance planner or maintenance engineer.

***Health, safety and environmental issue in the mine***

Risk analysis is normally performed in the mine and upgrading is done once a year. To ensure proper safety management, risks, incidents and accidents have been constantly reported and worked out, Table 4:5 show the number of risks, incidents and accidents that occurred from April 2010 to March 2011. The plan is to improve safety through the emphasis of immediate reporting of risks, incidents and accidents in the mine.

*Table 4:5 Accidents and risk/incidents in a year from April 2010 to March 2011*

<b>Year</b>	<b>Month</b>	<b>Accidents with absence</b>	<b>Accidents without absence</b>	<b>Incidents</b>	<b>Risks</b>
2010	Apr	0	0	1	1
2010	May	0	0	1	2
2010	Jun	0	0	1	0
2010	Jul	0	0	1	0
2010	Aug	1	1	1	0
2010	Sep	1	0	0	1
2010	Oct	0	0	0	3
2010	Nov	0	0	4	0
2010	Dec	0	0	7	1
2011	Jan	1	0	15	37
2011	Feb	0	0	23	56
2011	Mar	0	0	6	36
	<b>Sum</b>	<b>2</b>	<b>1</b>	<b>60</b>	<b>137</b>

Accident with absence - means that the accident caused job absence to the victim.

Accident without absence - is an accident that caused no job absence to the victim.

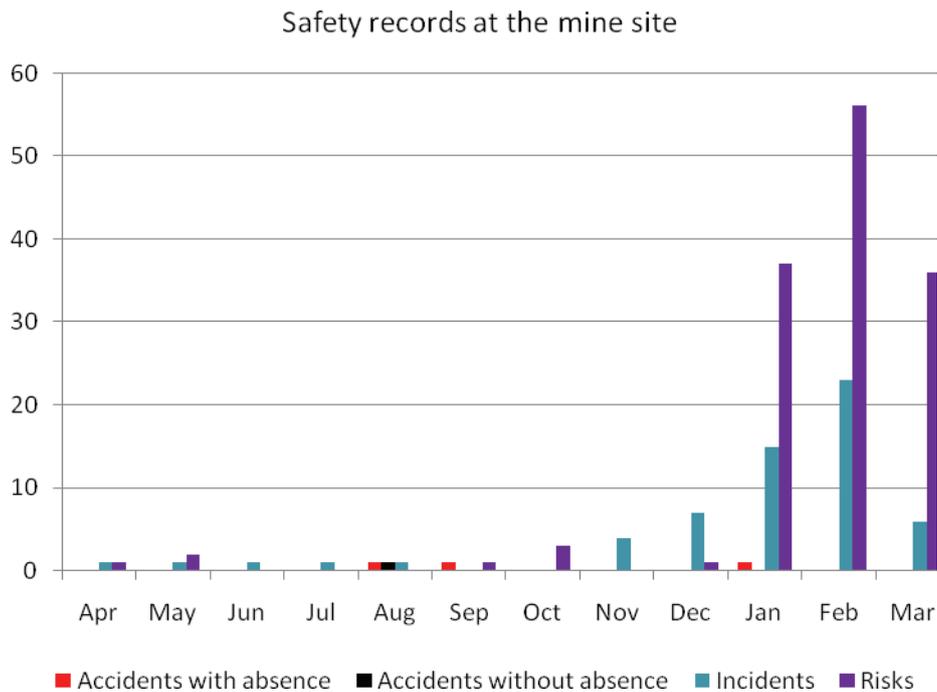


Figure 4:8 Safety records from April 2010 to March 2011

Figure 4:8 reveals the safety records in the mine from April 2010 to March 2011; records show that accidents with absence occurred in August 2010, September 2010 and January 2011. The last accident (with absence) occurred in January 2011. It also indicates that reporting of risks and incidents tendency was increasing from October 2010 where three risks were reported; the trend keep on increasing each month to march 2011, probably due to emphasis and attention paid to reporting safety related events. In addition to risks, incidents and accidents reporting, safety rounds are currently being exercised where every person has to visit 2 internal workplaces per year and the high ranked employees (managerial level) have to visit 15 workplaces per year. This is to see how regulations are being followed, how workers use safety gears and equipments, escape routes and assembly points as well as conduct some talks about some other worker's safety issues. But these rounds have not worked so effectively. To make it more workable they have decided to introduce an award system, although the employees mind seems not yet caught properly with the idea. Self commitment to work is the altitude needed to be given emphasis.

Emission control; There is an environmental protection policy standards for the mine, which shows the limit of permitted emission, the policy is effectively followed. The department has assigned a job to a person who tests each vehicle operating in the area. It is very rare for emissions level to exceed threshold. If the machine seems to endanger working environment it is withdrawn from working for fixing the problem, this can be done in the field/working area or in the workshop.

### **Existing Computerized Maintenance Management Systems (CMMS)**

Maintenance department at MalMBERGET uses three planning and scheduling softwares to run the operation activities. One of the systems software which is currently used is known as Wolis, this system is mostly for equipment data planning and reporting, it extracts data automatically from the machine to the server where it can be accessed via computer. Information such as number of loads, equipment ID, location etc can be captured easily by the system in a real-time manner. On the other hand quickview software gives the

maintenance cost data. Maintenance planner can sort the cost categories (highest or lowest) and go through them as per his/her requirement. The third software currently used in the mine is known as Movex, and is mostly used for resource planning, scheduling as well as for inventory control (material and spare parts). However interviewees are not comfortable of using the system, as it's not user friendly in the reason that it is not logical and it's difficult to work with. Data are also collected manually; one example of manually collected data is the equipment engine hours. It is taken every end of the week (Sunday) for each piece of equipment (LHDs). This weekly engine hour's collection is a time interval improved step as it was previously taken once in each month.

### ***Continuous reliability improvement and feedback***

The continuous reliability improvement system at the department is reactive in nature, meaning that the groups are formed when there is a rise of a problem. Formation of improvement groups or conducting discussions with the supplier while the problems have already occurred need to be reviewed. There is a need to ensure planned continuous equipment reliability as it is recommended by world class maintenance practices. Feedback is one of the very important tools in any organizational department. The feedback at the mine is not effective especially to the shopfloor level workers. There is a need to improve the feedback system.

### ***Major causes of equipments breakdown***

Major causes of equipments breakdown are as follows:

- Hydraulic system which includes hoses, valves, pumps and oil leaks.
- Equipments electrical systems
- Engine system
- Flat tires normally due to working environments (have rough floor with sharp stones), quality of the tires also need to be taken care of, and
- The filter blockage contributes to the equipments breakdown.

In addition, the preliminary risk analysis done by Gustafson et al., (2011), Figure 4:9, indicates that for semi automatic loader the most critical subsystem based on number of work orders are the hydraulics followed by the engine, electrical system, cabin and transmission while for manual loaders most critical subsystems are the hydraulics followed by the electric system, chassis, cabin and engine.

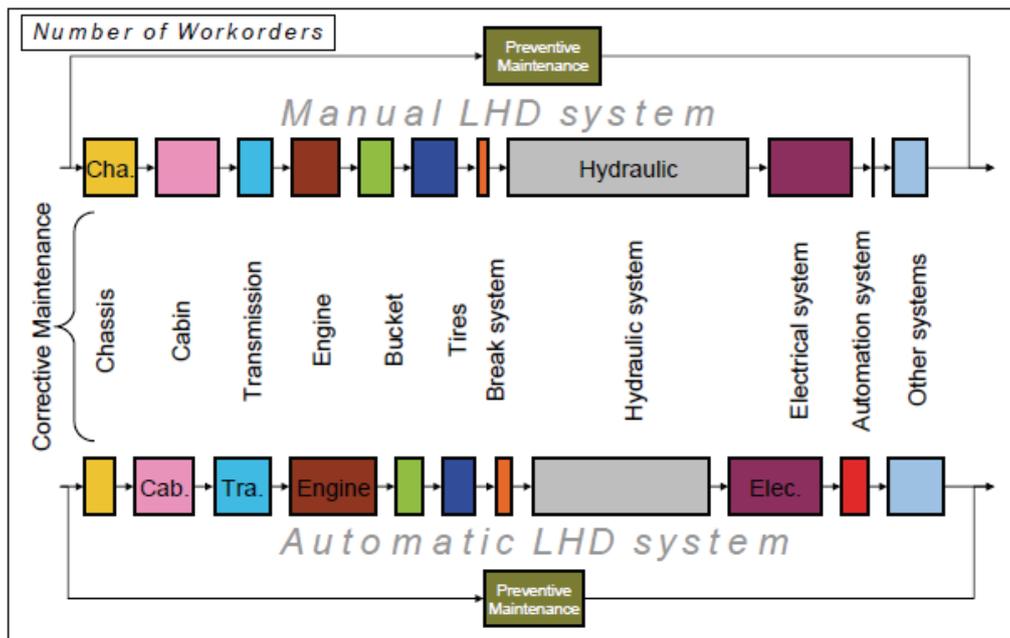


Figure 4:9 Critical subsystems based on number of work orders (Gustafson et al., 2011)

Occurrence of breakdowns especially the major breakdowns discussed previously affect maintenance planning budget to a great extent, and this is normally realized through increased maintenance cost/ton. The maintenance goal is 1.70 SEK/ton for LHDs. To facilitate targeted goals, three new LHDs were bought in October to December 2009. As an immediate solution materials/spare parts for systems like hydraulic systems, electrical systems, and engines are given high priority in the storeroom. Figure 4:10 below shows a storeroom equipped by hydraulic pipes and tubes together with other spare parts such as fittings, bolts and nuts.

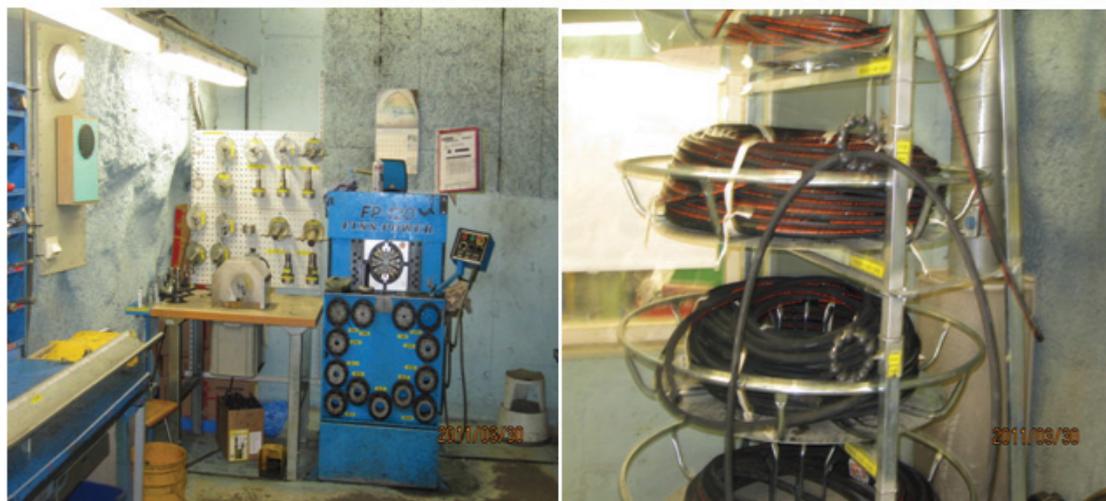


Figure 4:10 Underground storeroom equipped with hydraulic pipes and other spare parts and materials

### Education and training

There is training for maintenance planners and LHD operators, but it is not effective and properly planned. There is a need for effective training schedule and program in the department for the maintenance staff. LHD operators receives an on job training, the training in which it is given during normal working operations under the supervision of the experienced operator (trainer) within the mine and it is takes about two to three weeks

depending on how fast the trainee adapts the work. When the operator manages to run the machine he/she is given normal operation work as other experienced operators. Outsourcing is done in training for the case of new technology example for the semi automated LHDs, the maintenance training was given by the manufacturers, but this goes to an end as they have capacitated some of the workers in-site for maintaining the equipments.

**Maintenance strategies**

The maintenance strategy of the department follows the standard EN 13306, (2001). The department has some PM improvement plans, the plans includes collection of suggestions from the workers in the department, these suggestion should lead to improvement and savings to the department, the ideas are reviewed by the committee and by the help of the maintenance planner the savings potential are calculated and award is given to the person who made it. To look for better and cheaper manufacturer is among their focus. Inspection is conducted on daily bases at the start of each shift and this is done by the operator of the machine. For a better understanding of the maintenance process at the department the analysis of Corrective Maintenance (CM) and Preventive Maintenance (PM) data for machines (LHD C3 to C7 have been presented here under.

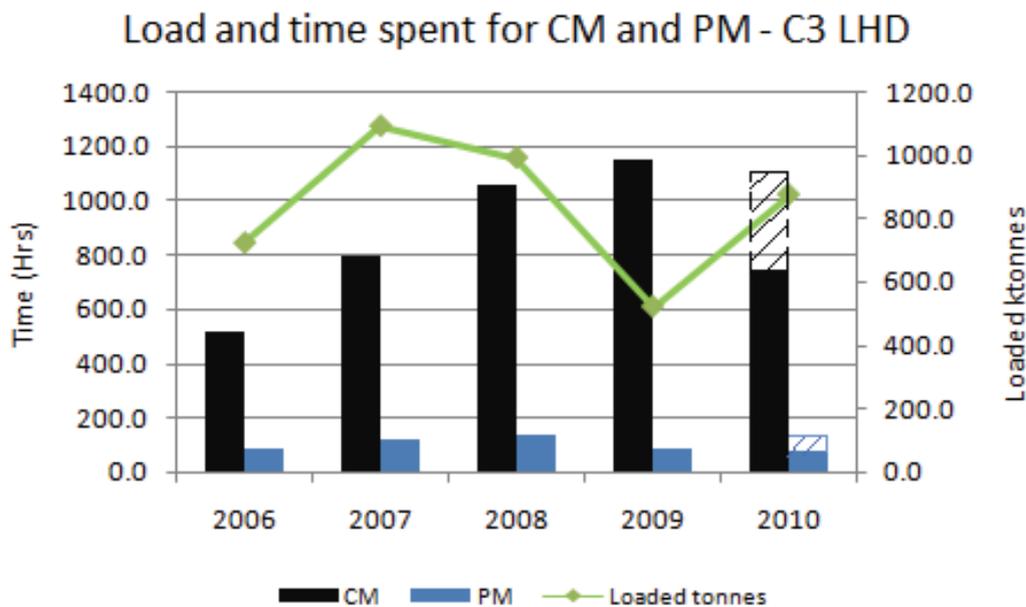


Figure 4:11 Time spent for CM and PM with loads for LHD C3 (2006-2010)

In all pieces of equipments C3-C7, it can be clearly seen that the amount of time spent for CM is higher than the time spent for PM. This means that high degree of attention need to be paid for corrective maintenance time. In analysis of the equipment above (LHD C3), (Figure 4:11), it can be clearly seen that the amount of time spent for CM is higher than the time spent for PM in all years of analysis that is from 2006 to 2010. This means that high degree of attention need to be paid for CM time. The trend shows that there is an annual increase of time spent for CM where the peak reached 1154 hours in 2009 while in the same year the amount of time spent for PM was 88 hours, implies that 93% of the down time was spent in CM. In addition to downtime hours, loaded tonnes were almost increasing with the increase of CM this is probably due to the fact that the more the machine is used the more it requires maintenance, but if these maintenance activities are not properly arranged results into more CM. In 2009 there was an abrupt drop of tonnes produced; this was due to the corrective maintenance (most of the time the LHD was in workshop) also due to production

stop in July caused by world economic crisis. The extended hatched part of the PM and CM bars in the year 2010 is the projection of the maintenance time. This projection was done because the available data ended in August (about 75% of the time of the full year).

For the trend of LHD C3, more work has to be done in planning so that to reduce the amount of time spent in corrective maintenance that will probably reduce the maintenance cost.

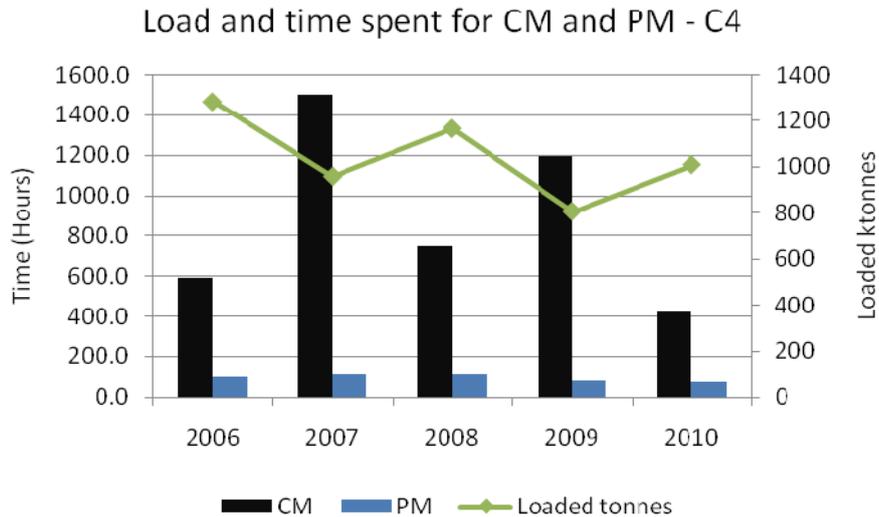


Figure 4:12 Time spent for CM and PM with loads for LHD C4 (2006-2010)

The machine C4 shows that CM are higher compared to PM throughout the year with the highest peak of 1503 hours of CM in 2007, in the same year (2007) the corresponding PM was 111 hours, implies that 93% of the downtime hours was spent in CM (Figure 4:12). In this Machine the increase in CM resulted into decrease in production as it can be seen in the year 2007 where the production decrease from 1285kt in 2006 to 959kt about 25% decrease of production in 2006. The same case happened in 2009 where the tonnes produced dropped from 1167kt in 2008 to 806kt in 2009 with CM time spent 749 hours and 1190 hours respectively.

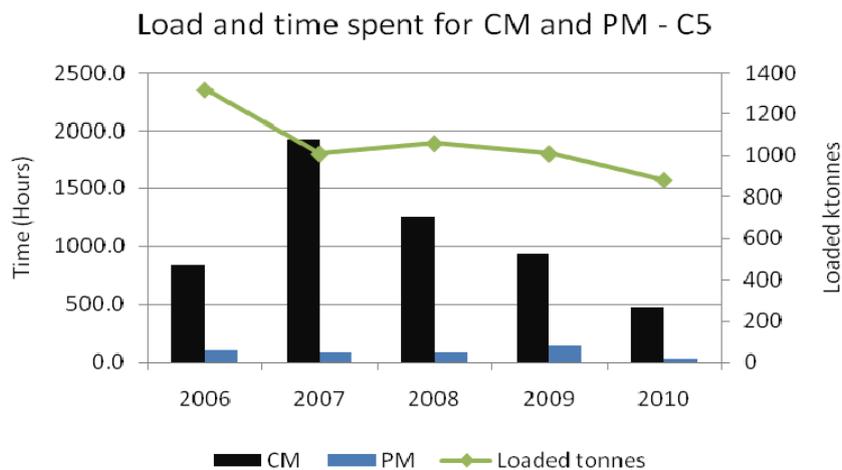


Figure 4:13 Time spent for CM and PM with loads for LHD C5 (2006-2010)

In LHD C5, the time spent for CM is higher compared to PM in all years but it decreases annually with an average of 36% from its peak of 1921 hours in 2007 to 475 hours in 2010, (Figure 4:13) showing that each year there is an improve in planning of the machine

maintenance. There is a small variations of annual production from 2006 to 2010, where in 2010 there was a decreased of 17 % of the average production.

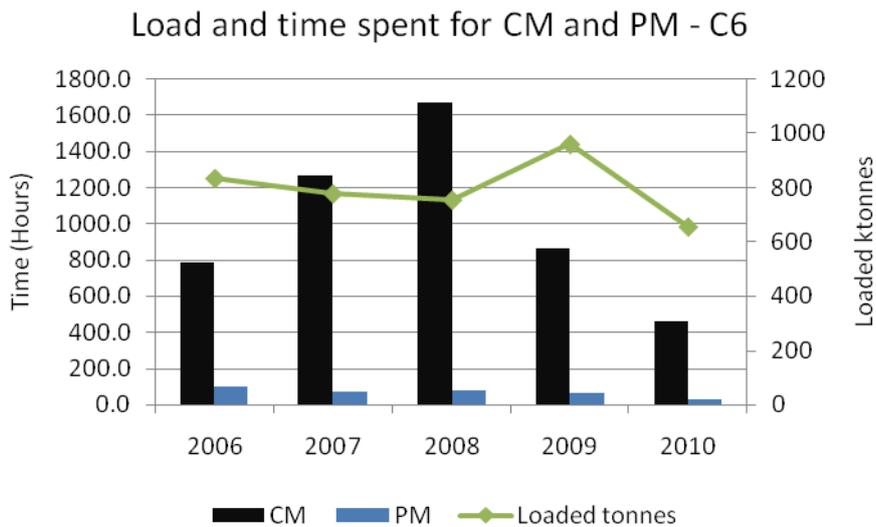


Figure 4:14 Time spent for CM and PM with loads for LHD C6 (2006-2010)

For LHD C6, the time spent for CM are higher than PM (Figure 4:14) the trend of time spent for CM was increasing from 2006 to 2008 while the PM was almost constant, this increase was probably caused by the component's failure rate increases with time, and thus likelihood of failure, also by non effective maintenance planning of the machine. But from 2008 to 2010 the trend of CM time spent tends to decrease from its peak of 1664 hours to 461 hours in 2010. In addition, production was decreasing in small degree from 2006 to 2010, but it abruptly peaked up in 2009, probably is contributed to proper and effective planning and control of the machine.

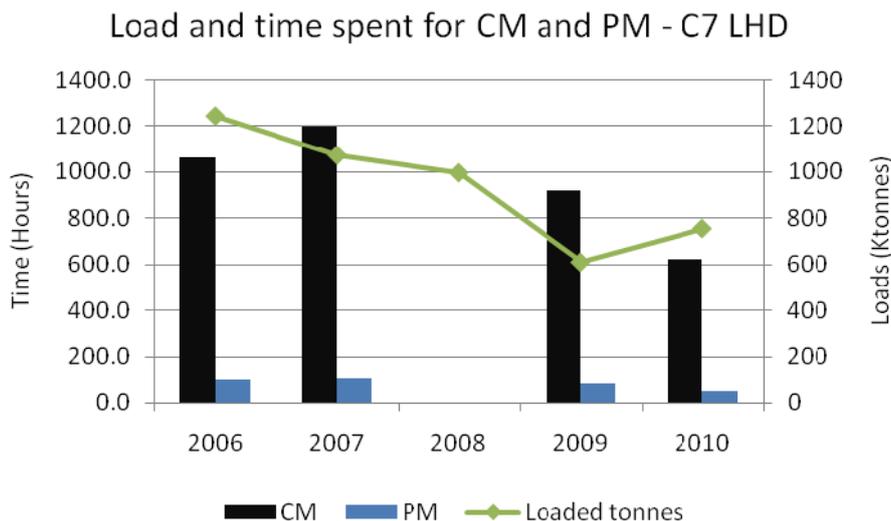


Figure 4:15 Time spent for CM and PM with loads for LHD C7 (2006-2010)

The time spent in CM for LHD C7 is more than 50 percent for all years of study (2006-2010) (taking CM time spent in 2007 as 100 percent) (Figure 4:15). Machine production was decreasing annually this was probably due to activities related to CM. In 2009 production was dropped to 610kt from 997kt in 2008, the reasons for the drop was that the machine did not operate in July and August.

#### 4.1.5 Machine hours and its corresponding loads

Machine hours and amount of loads carried by the machine plays an important role in determination of amount of time the machine has been in use and utilization of the equipment, the amount of time that machine has been in use can be a good KPI in maintenance activities. The two parameters above can help planner to be able to plan an effective maintenance interval for the equipment. The more the use of equipment the higher the possibility of developing failures hence require closely time interval for planned maintenance, this will results into effective performance of the equipment and will enhance production process . Table 4:6 below, shows the machine hours and amount of loads LHDs C3-C7 carried.

Table 4:6 Machine hours and loads for LHDs C3-C7 from 2006 to 2011

Machine ID	2006	2007	2008	2009	2010	2011	Total hours	Total(ktonnes)
C3	2136	3308	2981	2341	3327	0	14093	4212
C4	3445	3158	3550	2663	3271	896	16983	5227
C5	3638	2977	3331	3008	2734	831	16519	5268
C6	2622	2430	2482	2737	2232	767	13270	3981
C7	3333	3284	3099	2193	2633	706	15248	4682

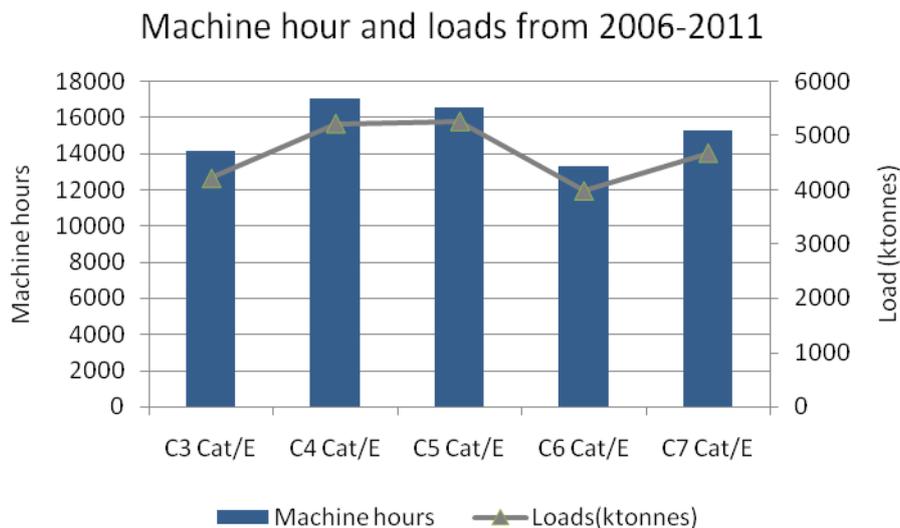


Figure 4:16 Machine running hours with its corresponding loads in ktonnes

Figure 4:16 shows that, LHD C4 has been used more than LHDs C3, C5, C6 and C7 also it has high number of loads carried, this may be contributed by its longer time of use compared to other LHDs for this reason operator and the maintenance planner has enough experience of the machine, in terms of operating and scheduling respectively. Figures also shows that LHD C3 has low number of loads and fewer number of machine hours, this may probably be due to the fact that the machine operates in manual and sometimes in semi automatic mode. So this alternation may cause some inconveniency in maintenance planning and operations.

#### 4.1.6 Conclusion

- The research work identified that hydraulic systems, electrical systems, engine, flat tires and filter blockages are the major causes of equipment breakdown.
- The evaluation of the maintenance problems currently existing at the mine maintenance department indicates that there is a lack of an effective training program to the staff members; therefore effective planned schedule for training is required. Regarding this, department has to think of giving timely based trainings to the workforce so that they can execute better procedures and practices required for maintaining equipments.
- Continuous maintenance improvement program is not practiced in the mine instead improvement groups are created temporary to fix a specific problem in hand. There is a need to have a continuous improvement program with improvement groups.
- Communication has been a problem, especially for the semi-automated LHDs and this was due to both electrical/electronic network system and the mechanical system of the equipment. Having good communication is essential especially for time and cost saving; therefore the department has to improve communication systems especially by upgrading the existing control network systems.
- Feedback was one of the identified problem in the department, this was two sided, the shopfloor workers do not receive feedback of the work performed and also the planners do not get the proper feedback from the performance indication measured data. The workers need feedback for the performance of their daily activities; this will act as the stepping stone towards their better performance.
- CBM is not effective as there is no improved instrumentation of the equipment to make it executed. Although to have CBM instruments involves some costs at the initial stages, it has proved savings when properly conducted and followed.
- High frequency at CM is a problem. This means that the department frequently face unplanned maintenance in their day to day activities which needs immediate solutions. Proper PM planning and scheduling can reduce the CM's high frequency.
- Expected completion time estimates for PM do not accurately reveal actual time observed. There is a need to work for the better and effective estimates of repair time.
- Factors such as delays caused by lack of resources example spare parts, material and labour, seems to control equipment downtime and not the actual repair time. Availability of resources needs to be over emphasised.

An evaluation of existing CMMS system of the mine identify that there is difficulties in working with the system as it is not logical and user friendly for planning, scheduling and inventory control. Making system logical and user friendly is very important for better productivity. White et al., (1991) suggested the use INTELLIMINE as a more reliable, logical and user friendly mine management system which will lead to gain in productivity.

## 4.2 Case study 2 – Barrick Gold Corporation (Tulawaka mine) Tanzania

### 4.2.1 Background to case study

The Tulawaka mine is located in northwest Tanzania, in the Biharamulo District of the Kagera Region, approximately 1,000 kilometers northwest of Dar es Salaam and 120 kilometres west of the Bulyanhulu mine. The mine consists of a completed open-pit mine with an underground access ramp located at the bottom of the pit. Tulawaka is a joint venture between African Barrick Gold and Northern Mining Explorations Ltd. Barrick holds a 70 percent interest and is the operator. In 2009, Barrick's share of production was 66,000 ounces of gold at total cash costs of \$413 per ounce, with Barrick's share of proven and probable gold reserves estimated at 93,000 ounces of gold. Tulawaka's life of mine as of December 31, 2009 was estimated to be approximately two years based on proven and probable reserves. According to Tulawaka responsibility report (2010) an updated mine plan based on the current successful underground mining is being prepared, which may result in an extension of the mine life,. The deposit is located within the Biharamulo Forest Reserve. Annual average temperature ranges between 25° and 40°C. Average annual rainfall is in the region of 860mm (Info Mine Inc, 2010). Figure 4:17 is the map of Tanzania showing location of the mine.

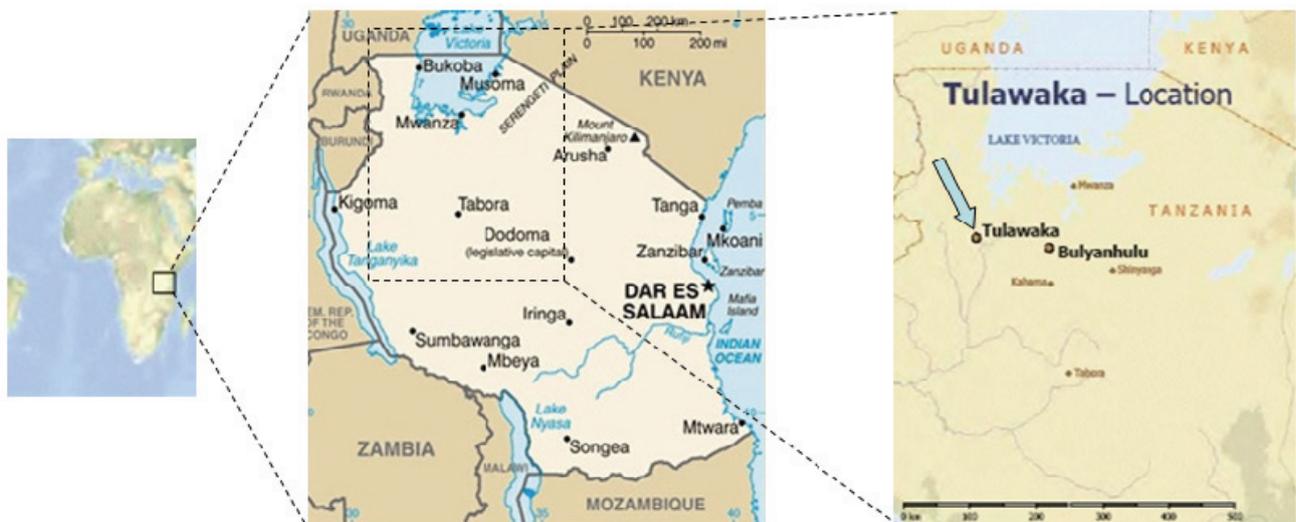


Figure 4:17 The map of Tanzania showing the location of Barrick Gold Tulawaka mine

### 4.2.2 Mining & Operations

Current operating capacity of the mill operations is approximately 1,320 tonnes per day. Total production in 2009 was approximately 94,000 ounces of gold at an overall recovery rate of 94.1 per cent. The operation and feasibility of mining ore body below the pit with underground methods is going on.

### 4.2.3 Available underground mobile equipment

The department deals with the service of the following mobile underground mining fleet which are currently centre of operation of the mine:

- 3 trucks
- 3 LHDs
- 3 Drill rigs
- 3 Tele handlers

#### 4.2.4 The organization chart at Tulawaka mine maintenance department

The outline of the maintenance department that ensures continuous equipment availability and operations is given (Figure 4:18) for understanding of the maintenance accomplishment process. Tulawaka responsibility report (2010) show that, the total number of workers of the mine is 400 with number of workers from contactors 335. The maintenance department has about 25 employees. Work is done in three shifts, namely, day shift from 6:00am – 3:00pm, afternoon shift 3:00pm – 11:00pm and the night shift which works from 11:00pm to 6:00am.

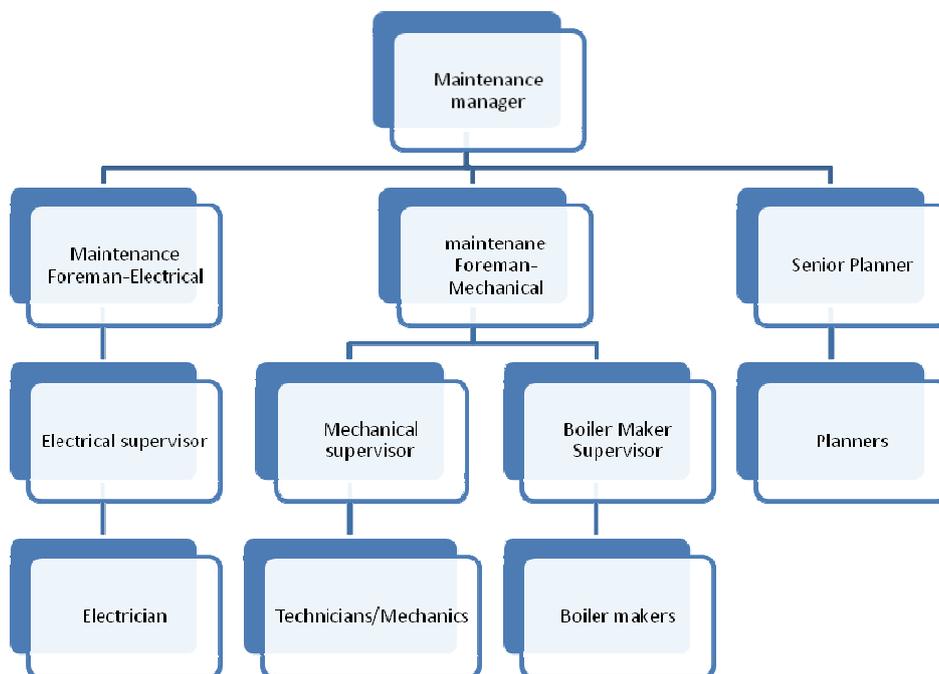


Figure 4:18 Maintenance department organization chart for Tulawaka mine (Tanzania)

#### 4.2.5 Results and analysis

##### *Workshops and services*

Currently the mine is not that deep to motivate an underground maintenance workshop and storeroom, although there is a plan to construct an underground workshop for minor repair and services. For that reason maintenance works are performed on surface where the central workshop is located. Location of the workshop was done following the requirements of the previous open pit mining activities. The central workshop is supported by the purchasing and warehouse units where material and spare parts are purchased and stored for the maintenance use in the mine. In addition outsourcing is performed as one of the external contract services at the department. The workshop uses team specialized in both surface as well as underground mining equipments.

##### *Material and spare parts flow and storage room capability*

The capacity of storeroom seem to be enough, however the consideration for expansion plan goes in parallel with the increase in production by buying some more equipments. The

supply chain starts from material requirements from the department, where by warehouse are contacted to check the material availability. If spare part or materials required are not available the quotation /proforma invoice for the items required from the selected supplier, raise purchase requisition from the system and send to supply chain to make follow up and deliver parts. Spare parts are ordered when not available in stock.

***The key maintenance performance indicators***

The main maintenance performance indicator at the mine is availability which has given first priority in assessing maintenance effectiveness at Tulawaka mine. It is important to note that all LHDs at the mine are manually operated, however the mine has a plan of introducing automated operation in future.

***Health, safety and environmental issue in the mine***

The philosophy of the maintenance department follows that of the company which needs that every person has to go home safely and healthily everyday. Barrick Gold Tulawaka mine is committed to achieving a zero-incident work environment with a safety culture based on teamwork and safety leadership. The company’s safety and health policy states that “nothing is more important than the safety, health and well-being of workers and their families”. The department implemented key safety programs and activities, including systems and policies, training for all crews, performance measurement, risk assessment processes, recognition programs for safety achievement, and a steady flow of information that keeps people focused on continuous safety improvement.

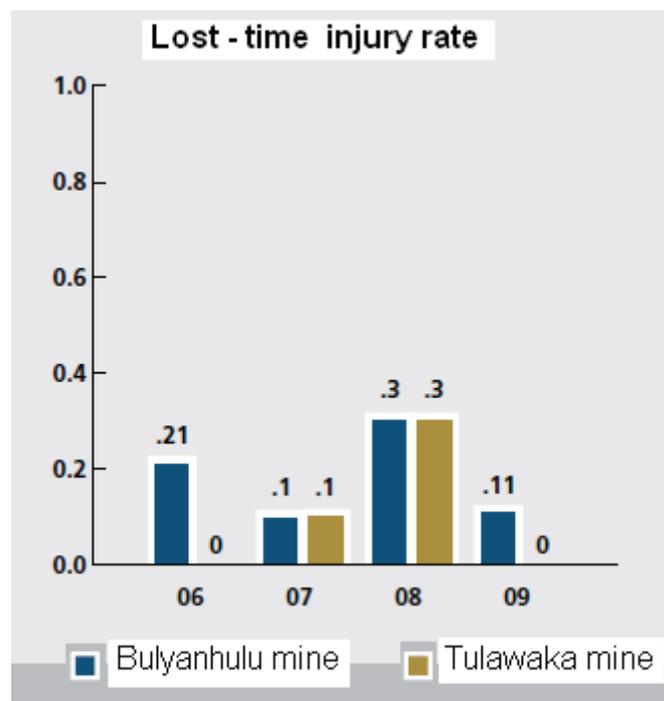


Figure 4:19 Safety records trend for Tulawaka mine from 2006 to 2009

Figure 4:19 above compares the safety trend of Barrick Gold Tanzania mines, Tulawaka and Bulyanhulu. The records shows that in 2006 there was no lost time injury, in 2007 the mine had 10% of lost time injury, lost injury increased by 30 percent in 2008 and this was due to activities related to switching to underground mining; the trend return to zero in 2009 showing a good record in the safety improvement. Emission in the mine is controlled by monitoring machine not to exceed the stated standard level of emission, if the machine seems

to cause environmental problems of any kind in the mine it is reported for maintenance and withdrawn from the work.

### ***Existing Computerized Maintenance Management Systems (CMMS)***

The mine uses pre-start check lists which is supposed to be filled by maintenance personnel on a daily bases. This information is fed into the maintenance data base system, which uses the maintenance management software package. The work is done by maintenance planning clerk at the department; in addition inspections information is also fed. Some of the entries needed in the data base are the machine engine hours from the start of each shift to its end, the amount of loads carried by the machine and the downtime hours during the working shift.

### ***Continuous reliability improvement and feedback***

To ensure continuous improvement of the maintenance process, the department provides feedback of the work and also receive feedback from production crew through the daily meeting which are conducted at the mine site.

### ***Major causes of equipments breakdown***

According to the interview results the major causes of equipments (LHDs) breakdowns at the mine are:

- Fluid pressures, oil leakages (hydraulic system problems)
- Electrical system defects
- Wear and tear caused by friction
- and expansion and contraction of materials

### ***Education and training***

The maintenance crew are trained in two ways; firstly, classroom training, whereby training is given in form of classes and or seminars, during training the crew is withdrawn from work site in order to attend the session. Normally involves learning some theories of the maintenance subject in question as well as conducting discussions regarding the subject. The second one is on job training whereby the worker is trained while working, this is done with the aid of the experienced maintenance worker.

### ***The main problems with the maintenance department are explained here under:***

#### ***Communication in the maintenance team***

There is poor communication among the maintenance crew; for example maintenance personnel can take time to communicate the equipment problem due to individual low know how capability of the problem in question. In addition the communication system itself sometimes tends to fail leading to breaking of the two way communication.

#### ***Technical reporting of maintenance downtimes and repairs***

There is lack of proper standards to communicate the problem in such a way that one problem can be communicated in different ways leading to the different understanding of the existing equipment problem, this has great impact in terms of time as well cost, crew have to drive to the field with undesired tools.

#### ***Lack of skilful manpower***

Some times the equipment problem becomes critical in such a way that it needs the presence of specialist either from the manufacturer or from external company (the need for maintenance outsourcing)

#### *Lack of tooling*

The department lacks some necessary tools in maintenance, examples of these tools includes the computerised maintenance management system, also working tools such as CBM tools for condition monitoring rather than depending on human sense.

#### *Data handling and organization*

There is a need to have a proper data handling system, sometimes checklist (filled paper) get lost on its way to the data clerk, this may lead to undesired results at the reporting time. In some cases the operators are in hurry and forget to collect their paper for picking up data for analysis.

#### ***Maintenance activities programs and strategies***

The department categorizes maintenance into four main blocks namely, planned maintenance, unplanned maintenance, corrective maintenance and condition monitoring. Preventive maintenance as a planned maintenance have been a key entity towards the successful implementation of maintenance practices at the mine, to ensure continuous availability and reliability department has put forward its improvement plans which are listed here under:

- Prepare Maintenance schedule based on hours interval
- Put in place the maintenance kits
- Conduct condition monitoring and oil analysis
- Perform pre and post PM inspection
- Put in place all proper tooling for maintenance activities
- Introduction of service report system

Future plans of the department to reduce downtime are anchored in the following issues;

- Backlogs to be completed and in timely manner during planning downtimes
- Educate operators to report all defects they see during operations, and plan for execution as fast as it can be done.
- Educate mechanics on inspection methods
- Introduce condition monitoring

#### **4.2.6 Conclusion**

The evaluation of the maintenance problems existing at the Tulawaka mine department indicates that;

- Communication has been a problem, especially for the system itself, in addition two way communications i.e. communication between maintenance crew has identified as a problem; to improve the system maintenance department needs to consider upgrading of the existing maintenance network system also to provide enough training for the crew to reduce ambiguities in communication.

- Feedback is there but need to be improved and also needs to be sustainable as when workers receive feedback from what they have done, act as a challenge which needs to be improved now and then.
- CBM is there but not in full swing, to make it more workable, department has to consider buying some CBM testing instruments also training LHD operators to use available means properly and correctly is an important decision.
- Reporting of downtime and repair has been a problem at the department, to avoid these the maintenance department has to think of providing standards procedure of reporting. In addition time to time training has to be given to staff and crew to on how to report technically.
- Lack of tools such as proper computerised maintenance management system results into inefficient execution of maintenance jobs. Further more, leads to ineffective planning and scheduling as well as unnecessary delays. In addition lack of working tools may lead to increasing idle time for workers. For this reason maintenance department has to make sure that proper tools are available at all times, which will increase working capability and hence productivity.
- Training has to be provided to maintenance personnel in their respective working area, and this training should be planned in such a way that an employee is updated with the new techniques and challenges in maintenance.

An evaluation of existing CMMS system of the mine identify that there is difficulties in working with the current system as it involved filling of data which is done manually by maintenance planning clerk, it is easy for the clerk to mess up and mix up some figures while putting them in the database. Also there is a need to integrate the systems such as purchase, production and maintenance so that information can be tracked easily.



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## 5. CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

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The two mines have differences in terms of capacities (technology, number of employee, number of fleet), the produced ore, environment etc. Regardless of the difference mentioned earlier there are some very important aspect which they share in the filed of mobile mining equipment procedures and practices. The following paragraphs explain the aspects in question that need to be paid attention to achieve a world class practises.

- In both mines, it has been identified that hydraulic systems are the major problem which leads to equipment breakdown, also electrical systems needs special attention in order to improve maintenance works and to reduce equipment breakdown. This can be done by choosing the proper manufacturer of the products.
- Departments also need to have plans on how to capacitate their workers in terms of time to time maintenance training in their respective area of specialization, this will help in better performance and efficiency in execution of their maintenance works.
- Feedback is not effective in all departments; workers need feedback to benchmark their performance. So these mines have to consider giving timely based feedback to their workers in order to enhance their departments.
- Communication has been a problem in both cases, and this has been seen in area of installed network system, meaning that the department has to pay attention in upgrading their maintenance communication system. In addition loss of information during communication due to different understanding of problem in question. On-job training should be emphasised at all levels from operators to maintenance managers.
- CBM is not effective in both cases; instruments necessary for performing CBM need to be readily available for use. This will lead to maintenance cost reduction when properly implemented.
- There was a limitation of the safety data for analysis in Tulawaka mine as they ended in the year 2009, so it becomes hard to come up with the recent trend to the year 2011. So there is a need for the department to update their database to have updated information in hand.

### 5.1 Future work

The research is limited to one type of equipment (LHDs) and case studies (Malmberget and Tulawaka mine). There is a need to explore further in maintenance procedures and practices in other underground mobile equipment types and mines.

Detailed analysis of the downtime factors should commence. This would call for a more detailed level of data recording. And this can be mostly done by the use of CMMS which would need a proper trained and data entry person.



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## APPENDICES

### Appendix 1: Interview Questions

#### LKAB – Malmberget Mine - Sweden.

1. *What are the major causes of equipment breakdown?*
2. *What are the main general problems you encounter in your day to day activities?*
3. *How do you normally solve the problems encountered in your day to day activities?*
4. *What can you say about your current equipment breakdown status and trend?*
5. *Does equipment breakdown affect your maintenance planning budget? How?*
6. *What have you done and what are your future plans to reduce equipment breakdown problems in your mine?*
7. *What is the current maintenance philosophy at your mine? ( Fail and Fix, PM, CBM )*
8. *Does a documented Maintenance Policy exist? Is it followed?*
9. *What kind of documentations regarding safety do you have?*
10. *What should be done to improve safety in your mine?*
11. *During which circumstances do you use external support maintenance team? How do you compare their cost with the internal support team?*
12. *Do you involve operators in maintenance? How is this conducted (in terms of reporting, handling, documenting, etc)?*
13. *What are your Preventive Maintenance improvement plans? Are they specific with timelines?*
14. *What is the maintenance time interval and/scheduling for unit mobile underground mining equipment?*
15. *How do you categorize maintenance? (Maintenance mapping)*
16. *What is the monthly cost of preventive and corrective maintenance? (2008-2011)*
17. *How many monthly man hours are spent for maintenance reworks and how much money do you spend for contract maintenance monthly? (Maintenance contract cost)*
18. *How do you control the flow of spare parts/Material? How is the supply chain organised, when and how do you order spare parts? Which criteria do you use to order spare part?*
19. *How do you capture data from the equipment for planning and reporting?*
20. *How and to what extent is the Computerised Maintenance Management System (CMMS) used? Who uses it? What are the limitations of the system?*
21. *Are you able to access historical information on the last time a system was serviced, by whom, and for what condition?*
22. *What kinds of spare part are frequently used for the maintenance works so needs to be stored mostly?*

23. *What kind of maintenance standards do you have? How do you measure and control emissions? What is the trend (percentage variation) of the measured emission from the standard allowed emission? (2008-2011)*
24. *What are your key performance indicators? Who is the person responsible for these indicators? How do you measure the performance?*
25. *How do you measure equipment effectiveness and reliability?*
26. *What are the means for improving equipment's effectiveness and reliability?*
27. *Do you have a continuous reliability improvement? How is it done at your mine?*
28. *How do you train operators? What kind of education programs do you have for them?*
29. *How do you motivate your maintenance team?*
30. *Define Preventive Maintenance (PM)? What are the tasks included in this PM?*
31. *Define Corrective Maintenance (PM)? What are the tasks included in this CM?*
32. *How many maintenance shifts do you have, how many hours allocated for each shift? How do you compare the working efficiency of these shifts?*
33. *How is the maintenance management system linked with the spare parts management system?*
34. *Do you have equipments maintenance handbooks/manual and standards?*
35. *How do you use maintenance handbook/manual for your daily maintenance activities?*
36. *What kind of regulations and procedures do you have to ensure that maintenance handbooks/Manuals are used during maintenance?*
37. *Do you get any feedback for your daily working performance? How do you get the feedback?*
38. *What are your key performance indicators? Who is the person responsible for these indicators?*
39. *Do you have a continuous maintenance improvement program? How do you do it?*
40. *Do you have operators based maintenance?*
41. *What are the main equipment operational problems you face in your daily activities?*
42. *What should be done to make the equipment operations effective?*
43. *How do you define Maintenance, may you categorize it? (Maintenance Mapping)*
44. *Are you involved with any maintenance, how?*
45. *Are you assigned the same specific machine daily? What is your comment about it?*
46. *Do you have any health problems caused by the working environment? What kind of problem?*
47. *What do you say about safety at your working area?*
48. *What instruments and techniques are you using for condition monitoring?*
49. *How often do you conduct detailed cleaning of equipments? How is it conducted? Are you a person responsible for it?*
50. *Do you have Equipments Maintenance handbooks/Manual and Standards*
51. *How do you use maintenance manuals for your daily maintenance activities (operator)?*

52. *What kind of training do you have, does it contribute anything in your daily tasks?*
53. *What does motivation mean for you (operator)?*

## Appendix 2: Interview results summary to some questions - Malmberget Mine - Sweden

1. *What are the major causes of equipment breakdown?*
  - Hydraulic systems which includes hoses, valves, pumps and oil leaks
  - Filter blockage
  - Flat tires
2. *What are the main general problems you encounter in your day to day activities?*
  - The biggest problem is the corrective maintenance
  - A number of unplanned breakdown
  - Oil leakage from equipments
3. *How do you normally solve the problems encountered in your day to day activities?*
  - Respond was fixing broken hoses and all small problems
4. *What can you say about your current equipment breakdown status and trend?*
  - the respond was that it is in the middle
  - The current trend is good as there is low number of breakdowns
5. *Does equipment breakdown affect your maintenance planning budget? How?*
  - Yes it affects the budget
  - Immediate results can be seen in cost(SEK)/ton
  - High maintenance cost and low produced tonnes
6. *What have you done and what are your future plans to reduce equipment breakdown problems in your mine?*
  - Emphasis in PM
  - Inspection and services at every 250,500,1000 and 2000 machine hours
  - Forming improvement groups when there has been a specific problem to solve.
7. *What is the current maintenance philosophy at your mine? (e.g., Fail and Fix, PM, CBM )*
  - To keep 9 LHDs operating.
  - To fix the failures when they happen, if failure seems to cause no damage then will waits for the next near future service
8. *Does a documented Maintenance Policy exist? Is it followed?*
  - It exist
  - Maintenance handbook, not being used.
  - Work mostly on routine.
9. *What kind of documentations regarding safety do you have?*
  - The respond was that they have risk analysis documents which are upgraded once a year.
  - They work a lot with safety, work environment, risks, and incidents so reports are written for every risk, incident and accident.
10. *What should be done to improve safety in your mine?*
  - Improve reporting of incidents, risks, accidents

- Have introduced safety rounds where every person has to visit 2 internal workplaces per year and the staff has to visit 15 per year for safety regulation follow up and discussion
  - Have a reward system
11. *During which circumstances do you use external support maintenance team? How do you compare their cost with the internal support team?*
- When there is too much work
  - When special competence is needed
  - When there is a lack of personnel
12. *Do you involve operators in maintenance? How is this conducted (in terms of reporting, handling, documenting, etc)?*
- Yes operators are involved in maintenance
  - Conducted by doing daily inspection at the start of each shift. The operator works with service man.
  - If there is a fault maintenance personnel is informed for further actions
13. *What are your Preventive Maintenance improvement plans? Are they specific with timelines?*
- They always look for better, cheaper manufacturers
  - In recent years they have started an inspection after the equipment wash
14. *What is the maintenance time interval and/scheduling for unit mobile underground mining equipment?*
- Machine service after 250, 500, 1000, 2000 engine hours.
  - Engine, converter, gearbox services done after 13000-14000 machine hours.
  - Transmission system after every 10000 machine hours.
  - Hydraulic pumps after 8000 machine hours.
15. *How do you categorize maintenance? (Maintenance mapping)*
- The same as the categorization in figure 2.2
16. *How many monthly man hours are spent for maintenance reworks and how much money do you spend for contract maintenance monthly? (Maintenance contract cost)*
- No clear answer for this
  - The big cost is the salaries.
17. *How do you control the flow of spare parts/Material? How is the supply chain organised, when and how do you order spare parts? Which criteria do you use to order spare part?*
- The inventory control is done by Movex software, so work order is done by Movex
  - Service man or maintenance planner place the work order
  - Manager approves the work order and sends it to purchase department for ordering
  - If material required immediately then calling is done and paper work follows
18. *How do you capture data from the equipment for planning and reporting?*
- Done automatically through a system called Wolis.
  - Manual reporting is done for machine hours only conducted every Sunday

19. *How and to what extent is the Computerised Maintenance Management System (CMMS) used? Who uses it? What are the limitations of the system?*
- Used throughout the department
  - Maintenance planners and engineers are the one who uses it
  - System limits its use as it is not logical and user friendly
20. *Are you able to access historical information on the last time a system was serviced, by whom, and for what condition?*
- Yes its possible
21. *What kinds of spare part are frequently used for the maintenance works so needs to be stored mostly?*
- Filters
22. *What kind of maintenance standards do you have? How do you measure and control emissions? What is the trend (percentage variation) of the measured emission from the standard allowed emission? (2008-2011)*
- Different maintenance standards including emission standards
  - There is a person working for testing vehicles.
  - Very rare to exceed the allowed standard emission level
23. *What are your key performance indicators? Who is the person responsible for these indicators? How do you measure the performance?*
- Costs, downtime, constant improvements.
  - Work environmental issues are a great focus for the maintenance manager.
24. *How do you measure equipment effectiveness and reliability?*
- Only availability is being used
25. *What are the means for improving equipment's effectiveness and reliability?*
- Improving PM, read machine hrs every week instead of every month.
26. *Do you have a continuous reliability improvement? How is it done at your mine?*
- Not systematic
  - It is formed when specific problem arise so it is temporary based.
27. *How do you train operators? What kind of education programs do you have for them?*
- Yes, on job training
28. *How do you motivate your maintenance team?*
- Division meetings, discussions, praise where necessary.
  - They have safety rounds where they can write the workers feelings.
29. *Define Preventive Maintenance (PM)? What are the tasks included in this PM?*

- Defined according to EN 13306, 2001
- Service, inspection after cleaning and repair after inspection.

30. *Define Corrective Maintenance (PM)? What are the tasks included in this CM?*

- Defined according to EN 13306, 2001
- Immediate CM must be done within 4 hours while deferred need time planning

31. *How many maintenance shifts do you have, how many hours allocated for each shift? How do you compare the working efficiency of these shifts?*

- 3 shifts: 06:00 - 14:24, 13:36 - 22:00 and 15:36 - 24:00(not weekends for the last shift)
- 5 persons/shift, there is no comparison for working efficiency for shifts

32. *How is the maintenance management system linked with the spare parts management system?*

- Through the same system (Movex)

33. *Do you have equipments maintenance handbooks/manual and standards?*

- Yes, but only the manufacturer's standards are being used. For Caterpillar there are DVDs and for Toro there are books.

34. *How do you use maintenance handbook/manual for your daily maintenance activities?*

- Uses the manufacturers standards rather often

35. *What kind of regulations and procedures do you have to ensure that maintenance handbooks/Manuals are used during maintenance?*

- None

36. *Do you get any feedback for your daily working performance? How do you get the feedback?*

- It is there but not effective

37. *What are your key performance indicators? Who is the person responsible for these indicators?*

- Key performance indicators are SEK/ton, MTTF, and downtime.
- Person responsible is a maintenance planner/maintenance engineer.

38. *Do you have a continuous maintenance improvement program? How do you do it?*

- No continuous improvement program.

39. *Do you have operators based maintenance?*

- Daily inspections

40. *What are the main equipment operational problems you face in your daily activities?*

- Communication cut off is the main problem (Semi-automatic machine)
- Difficulties when there are boulders (big stones), low utilization of the machine.
- Extra care should be taken for Ladar, small scratch can cause the machine not to function.

41. *What should be done to make the equipment operations effective?*
- The company should think of buying larger machines
42. *How do you define Maintenance, may you categorize it? (Maintenance Mapping)*
- See standard, figure 2.2
43. *Are you involved with any maintenance, how?*
- Yes, by doing the following: Daily inspection, like checking oils, lubrication, tires inspection etc.
44. *Are you assigned the same specific machine daily? What is your comment about it?*
- To be assigned a machine depend on which one is available, not always the same machine.
  - Better having one to two operators per machine to help in taking close care of it.
45. *Do you have any health problems caused by the working environment? What kind of problem?*
- Yes, the main health problems is neck and shoulders
46. *What do you say about safety at your working area?*
- Feel safe
47. *What instruments and techniques are you using for condition monitoring?*
- No special instruments
  - Listens, looks
48. *How often do you conduct detailed cleaning of equipments? How is it conducted? Are you a person responsible for it?*
- Operator cleans ladar (for semi automatic machine) at every shift
  - Cleaning is performed during service by maintenance personnel
49. *Do you have Equipments Maintenance handbooks/Manual and Standards?*
- Yes,
50. *How do you use maintenance manuals for your daily maintenance activities (operator)?*
- Is not normally used (mostly experience is used)
51. *What kind of training do you have, does it contribute anything in your daily tasks?*
- On job training when starting to work as operator (learn from experienced operator)
52. *What does motivation mean for you (operator)?*
- Salary, cake, etc.

### **Interview Questions Results Summary -Tulawaka Mine - Tanzania.**

1. *May you please describe the maintenance department organization structure?*

- Tulawaka mine maintenance department organization structure description is in Figure 4:18

2. *How many underground fleets do you have? How many LHDs?*

The number of underground fleets at the mine, including the number of LHDs

- 3 trucks
- 3 Loaders
- 4 Drills
- 3 Tele handlers

3. *What are the major causes of equipment breakdown in your mine?*

Major Causes of Equipments Breakdowns

- Fluid pressures, oil leakages (hydraulic system problems)
- Electrical system defects
- Wear and tear caused by friction
- Expansion and contraction of materials

4. *What are the main general problems you encounter in your day to day activities?*

Main problems encountered in our daily maintenance activities are:

- Availability of spare parts
- Man power for repair and service works
- No accurate information for machine downtimes

5. *How do you normally solve the problems encountered in your day to day activities?*

To solve the daily encountered problems the following steps are normally taken

- Order parts, adjust min/ max, put into stock items for parts we will need to use in the future which have never been ordered
- Work with priorities, advice the management to increase manpower
- Explain to supervisors and mechanics the importance of filling correct information

6. *Does equipment breakdown affect your maintenance planning budget? How?*

- Yes it affect in great extent because the department has to spend much money for buying spares

7. *What have you done and what are your future plans to reduce equipment breakdown problems in your mine?*

Future plans to reduce downtime

- Introduce condition monitoring

- Backlogs to be completed during planned downtimes
- Educate operators to report all defects they see during operations, and plan for execution as fast as it can be done.
- Educate mechanics on inspection methods

8. *What is the current maintenance philosophy at your mine? (Fail and Fix, PM, CBM)*

- Maintenance philosophy-Repair before Failure

9. *How is the safety trends look like at the mine? (Some data if available) 2008-10*

- Safety trend –Improving

10. *What should be done to improve safety in your mine?*

- To improve safety-Regular safety training in all mining employees and contractors

11. *What are your Preventive Maintenance improvement plans? Do you involve operators in maintenance? How is this conducted?*

Preventive maintenance improvement plans in hand are as follows listed below:

- Prepare Maintenance schedule based on Hrs interval
- Put in place the maintenance Kits
- Conduct condition monitoring and oil analysis
- Perform Pre and Post PM inspection
- Put in place all proper tooling for maintenance activities
- Introduce service report system

12. *What is the maintenance time interval and/scheduling for unit mobile underground mining equipment?*

- Maintenance time interval for unit mobile mining equipment is 250 hours, and weekly inspection.
- Also we have one week forecast scheduling.

13. *How do you categorize maintenance? (Maintenance mapping/diagram)*

- Planned maintenance
- Unplanned maintenance
- Corrective maintenance
- Condition monitoring

14. *How do you control the flow of spare parts/Material? How is the supply chain organised, when and how do you order spare parts? Which criteria do you use to order spare part?*

Control flow of spare parts

- Check availability in the ware house
- Check minimum and maximum
- Supply chain: Is from buyer to expeditor finally to the warehouse
- Spare parts are ordered when not available in stock.

How: Request the Quotation /Proforma invoice for the items required from the selected supplier, raise purchase requisition from the system and send to supply chain to make follow up and deliver parts

*15. How do you capture data from the equipment for planning and reporting?*

- Through Pre starts checklist
- Equipment inspection

*16. What are the main maintenance department problems?*

The main departmental problems are

- Poor Communication in the maintenance Team
- Technical reporting of maintenance downtimes and repairs
- Lack of manpower
- Lack of tooling